Bulletin
of
The Geological Society of America

VOLUME 63 February 1952 NUMBER 2

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Subscription $15.00 per year.

Publication Office: Mt. Royal & Guilford Aves., Baltimore 2, Md.

Communications for publication should be addressed to The Geological Society of America, Dr. H. R. Aldrich, Secretary, 419 West 117th Street, New York. N. Y.

NOTICE.—Four weeks notice of change of address is necessary. In accordance with the rules established by the Council, claims for non-receipt of the preceding number of the Bulletin must be sent to the Secretary of the Society within three months of the date of the receipt of this number in order to be filled gratis.

Entered as second-class matter at the Post-Office at Baltimore, Md., under the Act of Congress of July 16, 1894.

Accepted for mailing at special rate of postage provided for in Section 1103 Act of October 3, 1917, authorized on July 8, 1918.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 63, PP. 95-166, 15 FIGS., 11 PLS. FEBRUARY 1952

MOLLUSCAN FAUNA FROM THE PERMIAN KAIBAB FORMATION, WALNUT CANYON, ARIZONA

BY HALKA CHRONIC

ABSTRACT

During the summer of 1946, field investigations of the Alpha member of the Permian Kaibab formation were undertaken in the region of Walnut Canyon, south of Flagstaff, Arizona. Excellence of exposures greatly facilitated the measuring of sections and tracing of rock units along the canyon. Specimens were collected for lithologic analyses, and representative fossils secured from several zonules.

More extensive fossil collections were made at three exposures several miles north of Walnut Canyon, and at a fourth some 35 miles north. The fauna is analyzed and described, and an attempt is made to interpret the environment in which it developed and the conditions under which it was preserved. Environmental factors such as depth, salinity, temperature, and turbidity of the water, presence or absence of currents and other agitation, intensity of light, and the nature of the bottom are discussed. Conclusions reached indicate that the fauna, composed largely of mollusks, developed in a warm, shallow, epeiric sea not very far from land. A gradual retreat of the sea probably did not modify the depth of the sea very greatly. From low land to the northeast, fine sediments were brought into the sea, but it is believed that the water was not very brackish, except perhaps for short periods of time. The sea bottom was composed of a silty, clayey, calcareous mud containing abundant shells of dead organisms, and most of the smaller mollusks may well have lived attached to seaweeds and other marine growth, while larger and heavier forms crawled over or burrowed into the mud bottom. Periodic changes of conditions, probably due to oscillations in depth and a corresponding change in the nearness of the shore, brought about local extinction of the fauna and changes in the nature of the sediments.

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Introduction

Review of Literature

A consideration of the fauna and ecology of the Kaibab formation of northern Arizona was presented by McKee in 1938. His study of the fossils of the Kaibab, though the most extensive yet offered, was directed mainly toward analysis and description of the brachiopods of the Kaibab and underlying Toroweap formations. The molluscan elements were not described. Other discussions of Kaibab fossils are scattered and varied. Early collections by Gilbert were described by White (1877; 1879); trilobites from this region were the subject of an article by Joseph Snow (1945); several pectinids and myalinids were described by Newell (1937); and Nicol (1944) attempted a brief environmental study of elements of the facies discussed in this paper, but no systematic description of the molluscan fauna has been published.

Statement of Problem

This paper attempts to interpret more exactly than has heretofore been done the nature of the fauna and sediments of the Alpha member of the Kaibab formation in the area of Walnut Canyon, about 8 miles southeast of Flagstaff, Arizona. The area studied is bounded on the southwest by Lake Mary and extends northeastward about 7 miles, following the stream course. The region around Bottomless Pits, 3 miles north of Walnut Canyon, is also considered (Fig. 1).

The molluscan fauna of the Alpha member is described. In most of the natural exposures in this region, fossil-bearing strata of the Alpha member were not in evidence, apparently because fossiliferous beds are very porous and tend to crumble and form soil-covered slopes. In the region around Bottomless Pits, however, there are outcrops of these beds where fossil molds are readily collected. The rocks are exposed here in an erosion gully and two old railroad cuts. Supplementary material was obtained from a third locality, 35 miles north. Fossils from this locality are silicified and can be etched from the limestone in which they occur. A number of limestone blocks collected and etched at the American Museum yielded abundant material for study, and this was supplemented by collections loaned by the Museum of Northern Arizona and by the Grand Canyon National Park museum.

Localities and beds from which fossils were collected are:

Locality 1. Bottomless Pits. T 21 N, R 8 E, SW ¼ sec. 17.

Bed 2—fossils preserved as molds in dolomitic limestone.

Bed 9—fossils preserved as molds in dolomitic limestone.

Locality 2. Railroad cut. T 21 N, R 9 E, SW ¼ sec. 16.

Bed 4—fossils preserved as molds in dolomitic limestone.

Locality 3. Rimmy Jim tank. T 27 N, R 9 E, NW ¼ sec. 17.

Fossils silicified in limestone.

Acknowledgments

The writer expresses her appreciation to Dr. Norman Newell of Columbia University, Dr. Siemon W. Muller of Stanford University, and Mr. Edwin McKee of the Museum of Northern Arizona for guidance and valued suggestions in the preparation of this paper. Thanks are also due Dr. J. Brookes Knight for many suggestions relating to study of the gastropods,

Dr. Walter Bucher for aid in sedimentary aspects of the study, and the writer's husband, Dr. John Chronic, for advice and assistance and for critical reading of this paper. The privilege of using the Museum of Northern Arizona laboratories during the summers of 1946 and 1947, and the laboratories of the American Museum of Natural History during 1947–1949, is gratefully acknowledged. Permission to carry on research within Walnut Canyon National Monument was granted by the United States National Park Service, and collections of the Grand Canyon National Park, the Museum of Northern Arizona, and American Museum of Natural History were made available to the writer.

Stratigraphy

Physiography and Structural Geology

The Kaibab formation forms the surface rock of most of the Colorado plateau in the Grand Canyon area. The plateau is cut by numerous canyons, among which is Walnut Canyon, a narrow gorge some 400 feet deep carved through the entire thickness of the Kaibab formation and well into the underlying Toroweap. Although the stream course is somewhat tortuous, it runs in a general west-to-east direction. Throughout most of the canyon, steep walls and sparse vegetation combine with absence of any structural complications to make excellent sequences of exposures. Beds are, for the most part, completely shown in section from top to bottom, and can be correlated if necessary by tracing. In this study, however, where sections were measured only a few miles apart, correlation was usually possible by comparisons of lithology, fossil content, and weathering characteristics of the beds.

Except for a number of normal faults running in a roughly north-south direction so that they cross Walnut Canyon, the sequence of strata is not disturbed. In several places the stream has followed zones of faulting for short distances and in numerous places tributaries are subsequent to them. One of the largest of the faults, along the eastern shore of Lake Mary, forms an escarpment several hundred feet high and exposes the entire thickness of the Kaibab formation and the upper part of the Toroweap.

Throughout the length of Walnut Canyon, as well as at Lake Mary, strata are horizontal or very nearly so. Near Bottomless Pits, north of Walnut Canyon, a few degrees of dip were noted and taken into account when measuring sections there.

General Description of Stratigraphy

The stratigraphic relationships of the Kaibab formation as a whole have been described by McKee (1938), who divided the formation into three members:

The lowest, or Gamma, member was laid down when the sea was gradually encroaching upon the land from the west. The dominant rock type is a fine-grained limestone containing a molluscan fauna. It was deposited in water which was shallow and probably brackish, not very far from shore as the shore-line migrated eastward. It overlies the Toroweap formation, contact between the two being in most places level, though channelling and evidence of slight deformation have been observed.

The Beta or middle member was deposited at the time of the sea's maximum advance. In most areas Beta sediments are pure marine limestones, but in the Walnut Canyon area the rocks are fine-grained, silty to dolomitic limestones alternating with beds of chert. The fauna here is dominantly molluscan in contrast to a brachiopod fauna farther west. This lithology and fauna are interpreted as representing a near-shore environment.

Alpha member was formed as the seas retreated, so it also represents very near-shore deposition. Evidence indicates that conditions were not as stable, however, as during deposition of the Beta. Two rock types predominate: (1) a porous, fossiliferous, dolomitic limestone or dolomite which weathers rough and pitted, and (2) a nonfossiliferous, silty limestone weathering to smooth surfaces.

Over most of the Colorado plateau in the Grand Canyon region, the Kaibab formation forms the plateau surface, contact with the overlying Lower Triassic Moenkopi formation being present only at the margin of the plateau.

Stratigraphy in the Walnut Canyon Region

Along Walnut Canyon, several detailed sections of the Alpha member of the Kaibab were

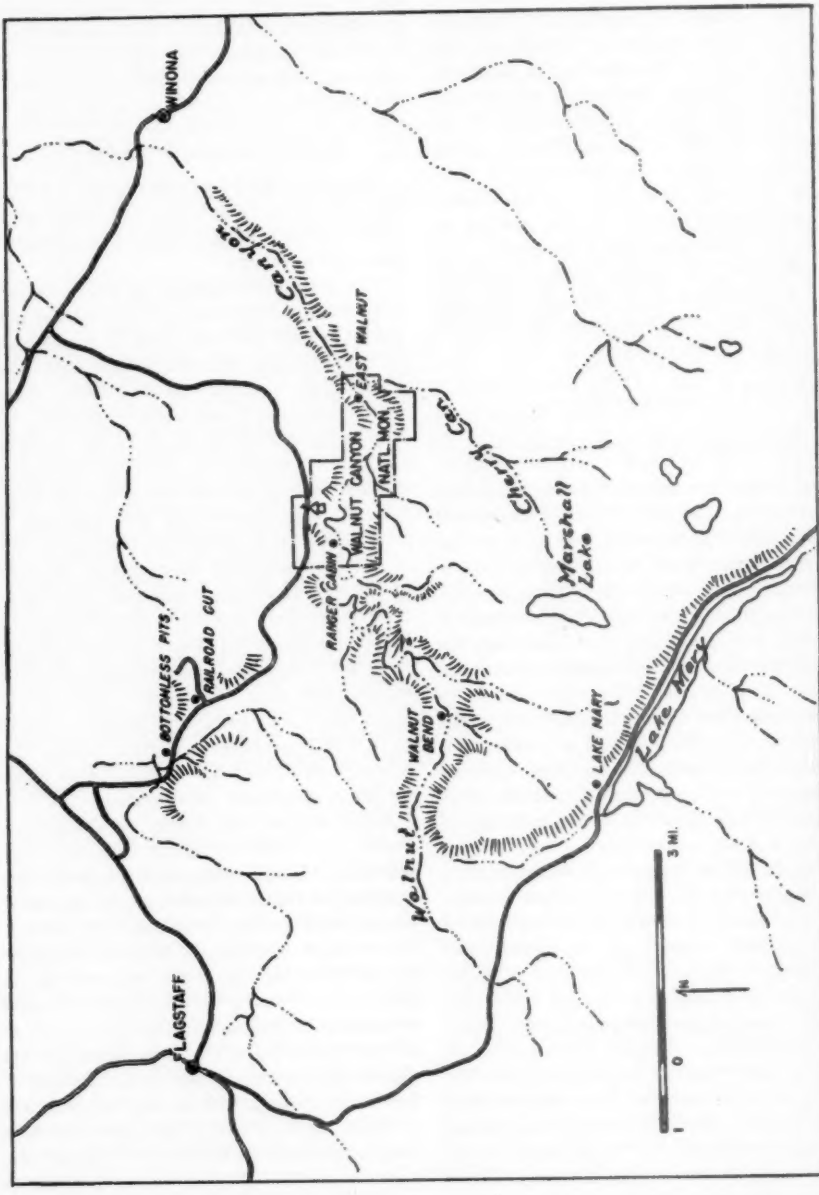

FIGURE 1.—LOCATION OF SECTIONS AND FOSSIL LOCALITIES

measured, forming, together with a section from the Lake Mary escarpment, an irregularly east-west line of sections. In addition to these, two incomplete sections near Bottomless Pits serve to locate fossiliferous beds in the lithologic sequence. The positions of measured sections are indicated on the map (Fig. 1) and sections are drafted (Pl. 11) and described.

In examining the stratigraphy in the area, it has been possible to correlate the various sections by means of several well defined key beds. One of these is a 3-foot bed which has been recognized at every section in Walnut Canyon and at Lake Mary. It is a fine-grained, pale-gray, silty limestone or calcareous siltstone, weathering to a two-tone effect showing laminations formed by ripples. In most places it is exposed as a smooth slope, free from talus, and so is easily identified.

Near the top of the section is a zone containing one or more of three distinctive types of rock. One of these is a limestone conglomerate made up of irregularly shaped limestone fragments. Another is a thick sandstone bed which forms the surface of the plateau in many regions. It is cream-colored and very fine-grained, but weathers to a red-brown color that is easily recognized. At its base, and also locally in another bed below, is the third type, a rather curious very fine-grained sandstone containing large, rounded, pitted sand grains in clusters or disseminated throughout. Because of the resemblance of the clustered grains to small fish eggs, this bed is referred to as the "fish-egg sandstone."

Rocks comprising the Alpha member in the area are primarily silty and dolomitic limestone, interbedded with calcareous siltstone and sandstone. The lower boundary of the Alpha member is well marked by an abrupt change of lithology, thickness of the beds, and weathering characteristics of the rocks. Rounded, massive, cliff-forming limestones of the Beta member give way to more thinly bedded limestones and dolomites of the Alpha member, which weather to a series of angular ledges with narrow slopes between. Bedded cherts, common in the Beta member, are lacking in the Alpha, though occasional chert nodules are present in the lower part. An examination of the vertical distribution of fossils shows a change in fauna at the same horizon as the lithologic change: the Beta fauna is dominated by *Dictyoclostus bassi* and *Plagioglypta canna*; the Alpha fauna is typically composed of an abundance of small mollusks with *Dictyoclostus bassi*, pectinids, and *Allorisma terminale* also present.

The lowermost 80 feet of the Alpha member are more resistant than overlying strata so that the beds form ledges and angular cliffs in the walls of Walnut Canyon, or part of the steep slope of the Lake Mary escarpment. At a rather well-defined horizon, the nature of the rocks changes and concealed slopes are formed. Only at the East Walnut section are these upper beds more completely exposed, and they are found to consist of alternating thin beds of fairly pure, silty limestone and fossiliferous, dolomitic limestone. The dolomitic limestone is porous and relatively non-resistant, and weathers in most areas to form a gentle slope to the top of the plateau. Chemical analyses of the fossiliferous dolomitic limestones from three localities at which fossils were collected are given below (analyses through the courtesy of F. G. Hawley):

	Loc. 1 bed 2	Loc. 1 bed 9	Loc. 2 bed 4	Loc. 3
CaO	29.8	31.2	30.7	24.2
MgO	19.3	19.8	18.9	12.2
SiO_2	4.8	2.5	4.7	29.2
Al_2O_3	0.28	0.36	0.09	1.16
Fe_2O_3	0.50	0.64	0.71	0.86

Analyses of silty limestone beds from approximately the same area are given by McKee (1938, p. 65, table 7a).

Above the series of limestones there is an abrupt change to beds of sandstone, associated locally with limestone conglomerate. The sandstone, which is not calcareous, suggests a late stage in the cycle of the sea's advance and retreat, and may represent the time when the sea had nearly receded from the land and deposits were being laid down in very shallow water close to shore. Locally the presence of large, rounded, pitted grains suggests that beach or dune sand, derived from the shore, was blown out to sea and deposited there with the water-transported material. Along new highway cuts a short distance to the east of Walnut Canyon, thick redbeds are interbedded with

FIGURE 1.—LOCATION OF SECTIONS AND FOSSIL LOCALITIES

light-colored sandstones and dolomitic limestones. These apparently represent the final stage of the cycle and fluvial deposition just previous to erosion of the pre-Moenkopi unconformity in this area.

Correlation of the Bottomless Pits and Railroad cut (locs. 1 and 2) fossil beds with the more complete sections obtained along Walnut Canyon is possible, as the "fish-egg" sandstone and conglomerate zone near the top of the Alpha is present in both localities. The two partial sections appear to represent approximately the upper 85 feet of the Alpha, with possible greater or lesser erosion of the few uppermost beds. This places the three main fossil-bearing strata in the lower half of the Alpha member, among those limestones and dolomites which in most areas form the upper part of the walls of Walnut Canyon. It is probable that the fossiliferous beds at locality 3 belong in the same approximate position.

Descriptions of Measured Sections[1]

LAKE MARY: Section on escarpment at north end of lake. T 20 N, R 8 E, NE ¼ sec. 18.

Top of plateau: Recent erosion surface.

Kaibab formation (Permian), Alpha member: units forming alternating series of silty limestones and fossiliferous dolomites.

	Feet	From base
13. Sandstone: very pale brown, very fine-grained with rounded, pitted, coarse grains scattered throughout; weathers light reddish brown; serves as marker bed (red "fish-egg" sandstone); forms slope to top of plateau.....	5.5	117.0
12. Conglomerate: weathers very pale brown; forms slopes; Matrix: purplish red, silty limestone (locally siltstone); Pebbles: irregular fragments of pink dolomite ½ to 2 inches in diameter.....	6.0	111.0
11. Concealed slope: contains: Limestone: very pale brown to pinkish white, silty; fossiliferous at 5.5 feet (mollusk fragments); ripple-laminated at 14 feet; forms weak ledges; Total...	22.0	89.0
10. Limestone: very pale brown to white, silty, porous; fossiliferous at base (large *Plagioglypta*, *Palaeonucula*, pectinids, other pelecypods) and at top (fenestellid bryozoans, mollusk fragments, *Palaeonucula*); forms partly concealed slope with weak ledges.....	13.0	76.0
9. Limestone: light gray grading upward to white; magnesian near base grading to silty at top; fossiliferous (abundant small, fragmentary mollusks, small cephalopod fragment, spines, bryozoan fragments); weathers light gray to grayish brown; forms series of weak ledges with occasional slopes.....	12.0	64.0
8. Limestone: pinkish white, silty, porous; like no. 10 but not fossiliferous; weathers gray; forms ledge.....	2.5	61.5
7. Siltstone: white, slightly calcareous (7% soluble in HCl), friable; beds thin (1–4 inches) and irregular; shows ripple marks (marker bed); forms slope and weak ledges; partly concealed....	3.5	58.0
6. Limestone: light gray to pink, silty, like no. 8; locally contains manganese dendrites; beds 1–4 ft. thick; weathers light gray to grayish brown; forms series of ledges; locally concealed.....	13.5	44.5
5. Limestone: light brownish gray, aphanitic, dolomitic, argillaceous, fossiliferous (mollusk fragments); forms slope; mostly concealed.....	2.0	42.5
4. Limestone: pinkish white, silty; like no. 8.....	4.0	38.5
3. Limestone: pinkish gray to light brownish gray, dolomitic, fossiliferous; like no. 5; contains scattered rods of white calcite near top; forms partly concealed ledges.....	19.5	19.0
2. Limestone: pinkish white, silty, porous; like no. 8; forms receding ledges.....	7.0	12.0
1. Limestone: pinkish gray, aphanitic, dolomitic; like no. 5; fossiliferous (abundant *Dictyoclostus*, *Marginifera*, *Palaeonucula*, *Bellerophon*, pectinids, Bryozoa); contains geodes and chert nodules; weathers light gray; forms series of ledges.....	12.0	
Total.....	122.5	

Beta member: units forming massive cliffs and slopes of silty limestone with chert nodules and interbedded chert.

WALNUT BEND. Section at bend of Walnut Canyon 3 miles west of old ranger cabin. T 20 N, R 8 E, NE ¼ sec. 5.

Top of plateau: Recent erosion surface.

[1] Grain sizes are according to the Wentworth scale. Color notations were obtained with soil color charts issued by the U. S. Dept. of Agriculture, 1946.

Kaibab formation (Permian), Alpha member:

	Feet	From base
10. Sandstone: reddish yellow, very fine-grained; contains coarse, rounded grains; weathers yellowish red; serves as marker bed (red "fish-egg" sandstone); forms slope	8.5	139.0
9. Concealed: slope containing series of weak ledges, mostly less than a foot thick, of: Limestone: white to light gray, magnesian, silty; locally fossiliferous (*Dictyoclostus*, *Plagioglypta*, fragmentary mollusks)	48.0	91.0
8. Limestone: pinkish white to very pale brown, magnesium, silty to argillaceous; very fossiliferous (abundant mollusk fragments); beds 1–4 ft. thick; forms retreating ledges (rim of canyon)	23.5	67.5
7. Siltstone: pinkish white to white, calcareous; locally fossiliferous (mollusk fragments); locally contains geodes and small calcite rods; forms series of receding ledges with concealed slopes between	12.5	55.0
6. Limestone: very pale brown, dolomitic; locally fossiliferous; contains partly concealed ledge of pinkish-gray, silty limestone near base; forms angular ledge with lower 3 ft. concealed	5.0	50.0
5. Limestone: light yellowish-brown, aphanitic, dolomitic, hard; beds ½–2 ft. thick; parting beds (1–6 in.) very pale brown, shaly, calcareous siltstone; forms cliff	8.5	41.5
4. Limestone: very pale brown, silty (11.8% insoluble in HCl), ripple-laminated; serves as marker bed; forms rounded ledges or slopes	3.5	38.0
3. Dolomite: pale brown, aphanitic; forms 3-foot ledge with concealed slope above	8.5	29.5
2. Limestone: pale yellow, dolomitic; like no. 6; beds 1–2 ft. thick; locally less silty and fossiliferous (abundant mollusk fragments); contains band of large chert nodules at base; forms steep angular ledge	8.5	21.0
1. Limestone: white to light gray, aphanitic, very silty; like no. 7; beds 2–4 ft. thick; contains abundant geodes in upper 2 ft.; forms ledges (6–8 ft.) with concealed slopes (3–4 ft.) between	21.0	
Total	147.5	

Beta member: massive cliff-forming limestone containing chert nodules, underlain by recess-forming chert.

WALNUT RANGER CABIN. Section in Walnut Canyon below old ranger cabin. T 21 N, R 8 E, SW ¼ sec. 26.

Top of plateau: Recent erosion surface.

Kaibab formation (Permian), Alpha member:

	Feet	From base
15. Sandstone: white to red, very fine-grained; weathers reddish-yellow to gray; serves as marker bed (red sandstone); forms much-concealed slope	12.0	118.0
14. Dolomite: reddish-yellow, aphanitic, argillaceous, hard; weathers white to light brown, rough, pitted; forms much-concealed slope	2.0	116.0
13. Sandstone: very pale brown, very fine-grained, calcareous; like no. 15; contains rounded grains of coarse sand scattered throughout; weathers reddish-yellow to gray; serves as marker bed (red "fish-egg" sandstone); forms slope, much concealed	3.0	113.0
12. Siltstone: very pale brown, calcareous, friable; forms slope, mostly concealed	3.0	110.0
11. Concealed: slope: contains weak ledges of fossiliferous magnesian limestone and dolomite	21.5	88.5
10. Limestone: white, silty, porous; weathers light gray, silty, smooth; forms thin ledges and concealed slope	8.5	80.0
9. Limestone: white to light gray, dolomitic, silty; beds ½–3 ft. thick; locally fossiliferous (mollusk fragments); forms cliff and retreating ledges (rim of canyon).	11.5	68.5
8. Siltstone: white, calcareous; like no. 10 but not porous; contains geodes; forms ledge	2.0	66.5
7. Limestone: pale yellow to light gray, dolomitic, silty; like no. 9; locally fossiliferous (mollusk fragments); contains small (½–¾ in.) calcite rods and irregular masses; basal 1.5 ft. concealed; forms cliff	9.0	57.5
6. Limestone: light gray, dolomitic, hard, brittle; slightly silty and white near top; weathers gray, pitted, irregular; forms cliff	3.0	54.5
5. Limestone: pale yellow to light gray, dolomitic, silty to argillaceous, aphanitic, hard (especially at top); like no. 9; weathers white to gray, pitted; forms ledges	5.5	49.0
4. Siltstone: white, calcareous (19.1% soluble in HCl), friable; like no. 8; weathers gray; forms slope, much concealed	2.5	46.5
3. Limestone: light gray to light brownish-gray, dolomitic, silty (especially near base); beds		

	Feet	From base
½–4 ft. thick; fossiliferous (mollusk fragments); weathers white to gray, rough, pitted, silty; forms receding ledges	16.0	30.5
2. Siltstone: white, calcareous (27% soluble in HCl); weathers white with wavy ripple laminae; serves as marker bed; forms recess or steep slope usually free of talus	3.0	27.5
1. Limestone: white, aphanitic, silty; beds 1–4 ft. thick; some beds magnesian and fossiliferous; contains vermilion geodes in upper part; weathers light to dark gray; forms retreating ledges	27.5	
Total	130.0	

Beta member: ledge-forming and cliff-forming calcareous siltstone and limestone with nodular and interbedded chert.

EAST WALNUT. Section ½ mile E. of Walnut Canyon National Monument boundary. T 21 N, R 9 E, NW ¼ sec. 31.

Top of plateau: Recent erosion surface.

Kaibab formation (Permian), Alpha member:

	Feet	From base
16. Sandstone: white to light reddish-brown, very fine-grained with scattered coarse rounded grains (red "fish-egg" sandstone); weathers red to grayish-brown; forms weak ledges exposed in slope to top of plateau	22.0	120.5
15. Limestone: very pale brown to pink, silty to argillaceous; forms slope, much concealed	7.5	113.0
14. Limestone: very pale brown, dolomitic, argillaceous, porous; beds 2–6 ft. thick; weathers very pale brown and very pitted; forms ledge (rim of canyon)	6.5	106.5
13. Limestone: white to very pale brown; alternates with: Limestone: light gray, dolomitic, fossiliferous (mollusk fragments); weathers gray, pitted; Total forms series of ledges and slopes	24.0	82.5
12. Sandstone: white, very fine-grained, calcareous, silty; beds thin (1–6 in.) and irregular; forms slope or recess	1.5	81.0
11. Limestone: white, silty; weathers buff to gray; alternates with: Dolomite: light gray, fossiliferous; Total like no. 13; forms ledge and slope	4.0	77.0
10. Limestone: light gray; like that in no. 13; beds thick (2–6 ft.); fossiliferous (abundant pelecypod fragments, a few bellerophontids); weathers gray, pitted; forms massive cliff	11.0	66.0
9. Limestone: white, silty; like that in no. 13; beds 1 ft. thick with irregular, wavy parting planes; forms recess	3.0	63.0
8. Limestone: very pale brown, mottled, very magnesian; beds 2–5 ft. thick; fossiliferous (*Astartella*, gastropods, small pectinids, small pelecypods); contains small geodes, esp. near top; weathers gray, pitted; forms massive cliff	9.0	54.0
7. Dolomite: gray, aphanitic, brittle, shaly toward top; contains much gray chert; fossiliferous (abundant *Schizodus* locally); forms slope	4.0	50.0
6. Limestone: white to light gray, silty, magnesian toward top of each bed; 2 beds 4 ft. thick; fossiliferous (*Dictyoclostus*, *Wellerella*, juvenile mollusks at top of lower bed, small mollusks in upper bed); forms ledge with basal bed locally forming recess	7.5	42.5
5. Limestone: white, silty; grades up into tan magnesian limestone containing mollusk fragments; beds 1–3 ft. thick; bedding planes wavy and irregular with thin parting beds of siltstone; weathers gray to black, angular; forms cliff	17.0	25.5
4. Limestone: white, very silty (36% soluble in HCl); shows ripple laminae (marker bed); forms bare slope or recess	3.0	22.5
3. Dolomite: light gray, silty, impure; contains 3-inch bed of calcareous siltstone at base forming slight recess; fossiliferous (*Pleurophorus albequus* very abundant, with both valves intact); forms slope	1.0	21.5
2. Limestone: white to light olive gray, silty and argillaceous (5.8% insoluble in HCl); very magnesian (progressively more so upward); beds 2 ft. thick; fossiliferous near center of each bed (*Palaeonucula*, scaphopods, juvenile and fragmentary mollusks); contains quartz geodes; forms series of ledges	11.5	10.0
1. Siltstone: white, argillaceous, calcareous; like underlying Beta member but beds thin (1–3 ft.); fossiliferous near center of each bed (small mollusks, incl. *Schizodus*, *Astartella*, *Palaeonucula*, bellerophontids; large pelecypods); forms series of retreating ledges	10.0	
Total	142.5	

Beta member: thickly bedded, massive, cliff-forming, silty limestones and calcareous silt-

stones with chert nodules, bedded chert, and thin beds of brittle, cherty dolomite.

RAILROAD CUT (Fossil loc. 2). Partial section at cut ¼ mile S. of Bottomless Pits. T 21 N, R 9 E, SW ¼ sec. 16.

Top of hill: Recent erosion surface.

Kaibab formation (Permian), Alpha member:

	Feet	From base
22. Conglomerate: forms slope. Matrix: yellow limestone; Pebbles: limestone fragments, irregular in shape, up to 8 in.....	2.0	82.5
21. Concealed: slope.....	2.0	80.5
20. Sandstone: very pale brown to yellow, very fine-grained; contains coarse, rounded grains in clusters; serves as marker bed ("fish-egg" sandstone).....	1.0	79.5
19. Concealed: slope.....	15.5	64.0
18. Limestone: brownish-yellow, aphanitic, silty; fossiliferous (abundant small pelecypods incl. *Dozierella*, *Promytilus?*); weathers very rough and pitted, locally pink, mostly yellowish-buff; forms weak ledges.....	4.5	59.5
17. Limestone: light gray, aphanitic, very argillaceous, hard and compact; forms slope, much concealed.....	11.5	48.0
16. Limestone: very pale brown, silty, magnesian; fossiliferous (abundant very small mollusk fragments); weathers silty, pitted; forms weak ledge.....	1.0	47.0
15. Limestone: light brownish-gray, magnesian; weathers gray, locally pink; forms slope, much concealed.....	2.5	44.5
14. Limestone: very pale brown, magnesian; weathers pitted, silty; forms ledge.....	1.5	43.0
13. Limestone: very pale brown, aphanitic, dolomitic, silty; locally grades to yellow siltstone; forms slope with weak rounded ledges.....	4.0	39.0
12. Limestone: white; weathers white; forms rounded ledge.....	1.5	37.5
11. Limestone: very pale brown, silty; forms slope, much concealed, with weak ledges.....	4.0	33.5
10. Limestone: light gray, magnesian; forms series of ledges ½–2 ft. thick.....	2.5	31.0
9. Concealed: slope.....	1.0	30.0
8. Limestone: light gray, magnesian; like no. 10; fossiliferous (mollusk fragments).....	2.0	28.0
7. Limestone: very pale brown, silty; like no. 11; locally fossiliferous (mollusk fragments); contains small silica rods up to ½ in. long; weathers pale brown; forms slope.....	11.0	17.0
6. Limestone: very pale brown, silty, magnesian; contains mollusk fragments; weathers same color to pink.....	1.5	15.5
5. Concealed: slope.....	3.0	12.5
4. Limestone: very pale brown, silty; very fossiliferous (see Tables 1, 2); weathers same color; forms ledge.....	6.0	6.5
3. Siltstone: white, calcareous, weak, sugary; locally contains quartz geodes.....	1.5	5.0
2. Limestone: very pale brown, silty; fossiliferous (fragments); forms slope.....	1.0	4.0
1. Limestone: white, magnesian, silty; locally fossiliferous (mollusk fragments); forms ledge.....	4.0	
Total exposed.....	84.5	

Base concealed by slope and valley alluvium.

BOTTOMLESS PITS (Fossil loc. 1). Partial section from sink up west side of valley. T21 N, R 8 E, SW ¼ sec. 17.

Top of hill: Recent erosion surface.

Kaibab formation (Permian); Alpha member:

	Feet	From base
23. Limestone: very pale brown, dolomitic; weathers light brown to gray, rough; forms slope to top of hill.....	5.5	92.0
22. Sandstone: pink, very fine-grained, silty; weathers gray to pink; forms ledge.....	2.0	90.0
21. Sandstone: white, very fine-grained; contains coarse rounded sand grains scattered throughout; weathers gray, pitted, irregular; forms marker bed ("fish-egg" sandstone); forms weak ledge.....	2.5	87.5
20. Dolomite: yellow to pale brown; weathers pale gray; forms slope.....	2.0	85.5
19. Sandstone: white, very fine-grained, silty; contains coarse rounded sand grains in clusters ("fish-egg" sandstone); forms weak ledge.....	5.0	80.5
18. Limestone: reddish-yellow, silty; contains coarse rounded sand grains locally; forms very weak ledge or slope concealed at base..	4.5	76.0
17. Sandstone: reddish-yellow to very pale brown, calcareous; very fine-grained; weathers same color; forms weak ledges much concealed.....	3.0	73.0
16. Sandstone: pink, very fine-grained, silty; weathers gray, rounded; forms weak ledge.....	1.0	72.0
15. Siltstone: very pale brown, argillaceous, calcareous; forms slope.....	7.5	64.5

	Feet	From base
14. Limestone: very pale brown, very silty and argillaceous, porous; somewhat fossiliferous; forms weak ledge	2.0	62.5
13. Limestone: light gray, magnesian, fossiliferous; weathers very pale brown; forms slope	4.0	58.5
12. Siltstone: very pale brown, argillaceous; like no. 15; weathers very pale to light brown, pitted; forms weak ledge concealed at base	7.0	51.5
11. Concealed: slope; at top contains: Siltstone: very pale brown, calcareous; like no. 15; weathers light gray; forms 3-ft. ledge; Total	16.0	35.5
10. Limestone: pink to pale brown; forms several weak ledges; locally much concealed	8.0	27.5
9. Limestone: yellow, dolomitic, silty, very fossiliferous (see Tables 1, 2); forms weak ledge	1.0	26.5
8. Limestone: yellow, fossiliferous (small mollusks); forms rounded ledge	1.5	25.0
7. Limestone: yellow, silty, fossiliferous (small pelecypods); weathers light gray, rounded, pitted; forms weak ledge	2.5	22.5
6. Concealed	3.0	19.5
5. Limestone: very pale brown, very silty and argillaceous; like no. 10; weathers brown	3.0	16.5
4. Siltstone: white, shaly (weak beds ¼–½ in. thick); weathers gray; forms recess	1.5	15.0
3. Limestone: light to pinkish gray, fossiliferous; beds 4–8 in. thick; weathers grayish-brown; forms ledges with sharp corners	1.5	13.5
2. Limestone: yellowish-brown to reddish-brown, dolomitic, slightly silty, very fossiliferous (see Tables 1, 2); weathers light brownish-gray; forms irregular slope or cliff	4.5	9.0
1. Limestone: light gray, fossiliferous; weathers purplish gray, rough	1.0	8.0
0. Limestone: pale yellow, silty; beds 1 to several ft. thick; weathers light brown; forms massive rounded ledge with base concealed	8.0	
Total exposed	97.5	

Base concealed beneath alluvium.

PALEONTOLOGY

General Description of the Fauna

The fauna of facies 3 of the Kaibab Alpha was described by McKee, (1938, p. 52, 153) as an impoverished fauna containing pelecypods, gastropods, and scaphopods as the principal forms, and as representing a near-shore, probably brackish-water environment. Nicol in 1944 discussed the nature of several faunules in the Flagstaff region and listed the genera occurring in them. His "*Dictyoclostus* faunule" corresponds in this paper to the fauna of bed 4, locality 2, and his "*Plagioglypta* faunule" to the fauna of locality 1, bed 9. Two other faunules have been added, that of locality 1, bed 2, and the silicified fossils found at locality 3, about 35 miles north of the other three localities, in McKee's facies 4 of the Alpha member.

The four beds from which collections were made were selected for several reasons. First, the strata at two of the localities were broken up in the construction of railroads for lumbering, and, as the rails have since been removed, the rocks are well exposed and offer ready collecting. Second, these four places appear to have a wealth of fossils not equalled in exposures along Walnut Canyon, except possibly at the easternmost section where the Alpha member is completely exposed. Also, collecting at these localities has been carried on over a period of years by the Museum of Northern Arizona, where extensive collections were available for study. Collections of the American Museum of Natural History included blocks of limestone from locality 3, which on etching yielded abundant silicified material.

Fossils from localities 1 and 2 occur as external and internal molds in aphanitic, slightly argillaceous, dolomitic limestones, and were studied by means of rubber squeezes. Fossils from locality 3 are silicified and occur in aphanitic or finely crystalline, silty limestone. They were exceptionally well preserved in amorphous white silica, and were freed from the matrix by leaching with hydrochloric acid. The excellent preservation and facility of collecting made it easy to obtain an abundant fauna which at first was thought to be closely similar to that from the other three horizons, but which on thorough study appears to differ markedly in general nature as well as detail. No section was measured at locality 3; the position of the fossils in the section is, however, believed to be approximately correlative with that of the other described faunules.

Chemical analyses of rock from the four zonules also reveal that, although at localities 1 and 2 the nature of the rock is very similar, the limestone at locality 3 differs considerably in proportion of magnesium and silica. The silica is largely secondary, and occurs as cavity fillings. It is not indicative of increased sandiness.

Study of the collections has added to and made many changes in Nicol's list (1944, p. 555), and new data have been obtained. Molluscan species identified by the writer are listed in Tables 1 and 2, with approximations of their relative frequencies in the four faunules under discussion. Frequency was determined by a survey of the collections and by actual counts taken from random blocks of rock.

The fauna of the four beds is dominantly molluscan, with gastropods and pelecypods leading in both diversity and abundance. Scaphopods, nautiloid cephalopods, and trilobites vary in their distribution, and bryozoans occur only as small fragments. Brachiopods are fairly abundant at localities 1 and 2, but are limited in variety. They occur only exceptionally at locality 3. A few crinoid arm plates occur at locality 3, but no other echinoderm remains are known.

Because of poor preservation and scarcity of bryozoans and cephalopods, they are not described here. Brachiopods from the western part of the Kaibab, including many forms known from the present localities, are described by McKee (1938). Trilobites from locality 1 were discussed by Snow (1945).

Thirty-seven gastropods are discussed in the present paper, belonging to at least 24 genera. Two forms could not be assigned generically. Three new genera and 22 new species are described; 13 forms are not assigned specifically. None of the gastropods have previously been described. The Kaibab gastropod fauna is markedly unlike most other Permian faunas of southwestern United States, being similar only to an as yet undescribed fauna from Word limestone no. 1 at the type locality in west Texas.

The pelecypods also bear a resemblance to the fauna of Word limestone no. 1. Twenty-six forms are recognized, representing 22 genera. Only 8 of the forms are new species, however; 13 species have been described before and 5 forms are not well enough preserved for specific identification.

Correlation of the Alpha member of the Kaibab with lower Word is suggested by the strong resemblance of such pelecypods as *Kaibabella curvilenata*, *Astartella subquadrata*, and *Grammatodon politus*, and such gastropods as *Retispira undulata*, *Warthia* sp., *Worthenia corrugata*, *Stegocoelia quadricostata*, *Euomphalus kaibabensis*, *Glyptospira cristulata*, *Orthonema striatonodosum*, and *Oncochilus insolitus*.

Gastropods and pelecypods are, in general, represented by small individuals, usually less than 15 mm. in greatest dimension. In each faunule, however, one or more large forms occur. At locality 1, bed 2, an occasional *Allorisma terminale* or *Aviculopecten kaibabensis* stands out in contrast to many tiny forms. At locality 1, bed 9, the prominent large form is *Allorisma terminale*, and *Aviculopecten kaibabensis*, *Aviculopinna sagitta*, and *Murchisonia geminocarinata* also reach considerable size. Bed 4 at locality 2 is dominated by the large brachiopod *Dictyoclostus bassi*. At locality 3, large and perfectly preserved specimens of *Bellerophon deflectus* are common. Fragments of nautiloid cephalopods at locality 1, bed 9, and at locality 3, suggest that these forms were probably the largest hard-shelled animals in the Kaibab Alpha sea. Large specimens must have had a body chamber diameter of several inches.

In the lower faunule (bed 2) at locality 1, the dominant forms are *Astartella subquadrata*, *Pleurophorus albequus*, and *Palaeonucula levatiformis*. Gastropods, although varied, occur only in small numbers. Pelecypods abound, but are more limited in variety.

In bed 9, at locality 1, the fauna is markedly richer. Both pelecypods and gastropods are abundant and varied, and *Plagioglypta canna* is also common. Individuals of almost all the species are larger and perhaps more mature than at other localities. Fossils appear less fragmentary than in the other beds. Although almost or entirely absent in other faunules, high spired gastropods such as *Murchisonia geminocarinata* are present at this locality and sometimes reach considerable size. The large pelecypod *Allorisma terminale* commonly occurs in groups, as does *Plagioglypta canna*. Brachiopods are common, but do not dominate

the fauna. A number of cephalopods have been collected from this horizon, and trilobite pygidia are fairly common.

Locality 2, bed 4 is exceptional in its almost complete lack of gastropods, as well as in the abundance of the large brachiopod *Dictyoclostus bassi*. Many elements of the pelecypod fauna are obviously juveniles. The gastropod *Retispira undulata* may also be represented only by juveniles, as larger individuals, seemingly of the same species, are known from collections from the Word limestone now at U. S. National Museum. Another unusual feature of this faunule is the complete absence of *Astartella subquadrata*, which is exceptionally abundant in the other three faunules, and has been recognized in quantity in many beds of the Alpha member.

At locality 3 the fauna is diversified and abundant, containing pelecypods and gastropods in almost equal number. The absence of brachiopods is noteworthy, though *Dictyoclostus bassi* has been found occasionally. The gastropod *Glyptospira cristulata* is more common here than elsewhere. This is the only locality at which echinoderm remains have been found: numerous crinoid arm plates and a few columnals were obtained from the siliceous residue.

In summary: the four zonules all contain molluscan assemblages, but the composition of the faunas varies rather widely. This variation probably parallels a variation in environmental conditions, physical or biological, but may be partly due to a variation in time. Genera common to all three faunules are thought to represent hardy forms tolerant to a greater range of environment, while those present within only one or two faunules are absent elsewhere because conditions were not quite favorable. By an analysis of the physical environment as recorded in the rocks and fossils we may hope to ascertain the nature of the Kaibab Alpha seas, and the similarities and differences of the environment of deposition of the four faunules under discussion.

Paleoecology

In any study of marine environments, many ecological factors must be considered. In modern seas most of these factors are easily measured, but for ancient seas, represented today only by marine sediments and fossils, exact measurements are not available. A picture of the ancient environment can be obtained only by summation and interpretation of information gleaned from the fossils and sediments.

A comparison of fossil genera from the Kaibab with recent related animals of similar form and structure supplies many clues to the nature of the ancient environment in which the fossils lived, assuming that in most cases, at least, an animal of today lives in an environment more or less similar to that inhabited by its close relatives of the past. Accuracy is, of course, limited by the only distant relationship between Kaibab and modern forms.

Paleoecological interpretations of this nature are also limited by the amount of data available on living forms. Most studies of marine ecology place emphasis on biologic factors, and although these are also considered here, they are difficult of interpretation in fossil faunas. Biologic factors do not seem less important to an understanding of the fauna than physical factors, but data of marine biological researches are not available in a form convenient for the geologist, and a synthesis of what is known of environments and their effects on animals is badly needed.

Another limitation on inferences of past environment from analogy with modern forms lies in the fact that transportation after death is a common occurrence on any sea floor where current or wave action is present. Within the Kaibab Alpha, however, evidence of such action is lacking, and shells are not believed to have been transported far from their original habitat. The two valves in pelecypods are frequently not separated, and the presence of broken and fragmentary shells, though suggestive of agitation, may be attributed largely to the activities of predators, scavengers, and other burrowing animals.

Certain features of the fauna as a whole indicate characteristics of the environment. The small size and delicate ornamentation of individuals of several groups, for instance, is thought to indicate a mode of life contrasting with that of large, thick-shelled, smooth-shelled individuals which occur in the same faunule.

Thickness of shell, general size and shape, and characters of ornamentation might be useful in determining depth, temperature, and other factors, but here again lack of tabulation of biologic knowledge for use in geological research is evident.

Although geologists are not all agreed on the conditions of deposition of certain types of marine sediments, some aspects of sedimentation serve as excellent guides to an understanding of paleoecology. Ecological factors inferred from the sediments are turbidity, agitation, nature of the bottom, temperature, and, to a limited extent, depth and distance from shore.

Using all available information, it has been possible to draw the following conclusions regarding the environment of the Kaibab Alpha fauna, represented by the four faunules listed above.

BOTTOM: The nature of the rock suggests that the sea floor was covered by a calcareous mud. Examination of thin sections from the four localities indicates that this mud was largely made up of broken and finely particulate shell material, with perhaps a minor amount of chemically precipitated calcium carbonate. The shell fragments were probably derived frem animals living on and in the mud, and includo fragments of foraminifera. The shells are thought to have become broken through the action of burrowers and scavengers rather than through wave action, as there is no evidence of sorting.

Treatment of samples from the four zonules with dilute HCl has yielded residues in the following proportions.

	Loc. 1 bed 2	Loc. 1 bed 9	Loc. 2 bed 4	Loc. 3
% insoluble (by weight)	6.4 6.6	2.7 1.6	5.8 5.1	30.0 32.6

The residues are composed largely of fine white silt with an admixture of clay. The clay at loc. 1, bed 2, and loc. 2, bed 4, is grayish brown, and in bed 9 at loc. 1 it is orange-brown, appearing in all three cases to have caused the color of the rock. The residue at loc. 3 is made up almost entirely of silicified shell material, irregular particles of chert, and sponge spicules. There does not seem to be more sand or silt present in residues from locality 3 than in those from localities 1 and 2.

It is obvious that the *Plagioglypta* faunule at loc. 1, bed 9, existed in an environment containing less insoluble detrital material than did the other environments.

The evidence for a bottom composed of fine muds is supported by a study of some of the fossils. The abundance of fossils in itself may be significant, as a mud bottom supports a larger number of individuals than does any other type. *Nucula*, modern relative of the Permian form *Palaeonucula levatiformis*, burrows in fine sand or silt, feeding below the surface, and *Nuculana*, present in both Permian and modern seas, also prefers a mud substratum (Yonge, 1939, p. 82, 83). The presence of the long-spined *Dictyoclostus bassi*, as well as other spine-bearing brachiopods, likewise suggests a muddy bottom, as indicated by Cooper's observation (1937, p. 45) that productids were supported above a mud bottom by their spines, in such a manner as to keep their margins above the mud. Cooper also observed that geniculation of the shell, common in productids, in similar manner served to keep the margin of the shell above a mud surface. Modern scaphopods are known to burrow in mud, and it is likely that Permian forms did also. The selenizone of *Bellerophon deflectus* probably supported a siphon, which was extended above the surface as the animal moved in the mud.

Cyclic development of dolomitic, fossiliferous limestones alternating with silty, nonfossiliferous limestones indicates a periodic variation in the composition of the bottom muds. The silty limestones probably represent changes in depth and nearness of the strand line. Occurrence of abundant similar silty limestones in the Beta member suggests that they represent deeper water than do the dolomitic limestones. Although their present silty texture might suggest origin close to shore, shell material included in the dolomitic limestones formed a much coarser clastic.

DEPTH: A shallow-water environment (less than 100 fathoms, often less than 200 feet) is suggested by Cooper for Paleozoic epicontinental seas in general (1937, p. 38). There is considerable evidence supporting a shallow-

water origin for the Kaibab Alpha member. The sea in which the Kaibab formation was laid down transgressed from the west, and the land over which it came was low and level (McKee, 1938, p. 147–150). In the open sea, pure, thick-bedded limestones were laid down; nearer shore, the limestone became silty and then dolomitic, and finally gave way to sandstone of eolian origin. Even during the maximum advance of the sea, the strand line could not have been more than 70 miles east of the Walnut Canyon region, though the sea may have extended farther southeast. As the sea retreated, while the Alpha member was being deposited, the strand line migrated westward so that the shore line progressively approached the Walnut Canyon area. With the approach of the shore, there must have been a corresponding decrease in depth, which could at no time have been very great because of the flatness of the land.

Dolomitic limestones containing fossils suggest accumulation on the bottom of very shallow seas, and the low proportion of insoluble clastics and lack of indication of agitation suggest that the limestones may have been deposited in partially land-locked basins. Conditions controlling the formation of dolomite are subject to much disagreement, but it is believed that dolomitic limestones of the Kaibab formation definitely originated in shallower water than did purer limestones farther west. This conception is supported by the relative position of dolomitic limestones in the stratigraphic section: they cocur near the base and top of the section, in members Gamma and Alpha, which represent the incursion and withdrawal of the seas. Dolomitic limestones do not occur in the Beta member, which represents the greatest advance of the sea and therefore was deposited at the greatest depth.

There was undoubtedly much fluctuation of depth during the time of deposition of the Alpha member, and it brought about cyclic development of alternating beds of fossiliferous dolomitic limestone and nonfossiliferous, silty, nondolomitic limestone. The silty, nondolomitic limestones occur more abundantly seaward and seemingly represent somewhat deeper water than the dolomitic limestones.

The nature of the fauna supplies further evidence that the sea was shallow. Gastropods and pelecypods are known to be relatively rare or absent in seas of today over 80 or 100 fathoms in depth. Nomura and Hatai (1936) have listed depths of several forms which are represented in the Kaibab Alpha by related forms. Pectens were observed to range from about 50 to 225 meters, scaphopods from 50 to 215 meters, and *Nuculana* from 160 to 220 meters. *Nucula* and *Natica*, modern relatives of *Nuculopsis* and *Naticopsis*, were dredged from 84 meters. Newell's examination of the environments in which Mytilacea live today led him to state that "Late Paleozoic Mytilacea favored the shallow-water near-shore habitats like those preferred by the majority of modern Mytilacea" (Newell, 1942, p. 14). Modern scaphopods usually live in fairly deep water, but their range is from two to more than 2400 fathoms. Shimer and Shrock (1944, p. 521) believe that fossil species probably lived at moderate depths.

Negative evidence may be found in Agassiz's observation that calcareous and horny sponges are replaced below 100 fathoms by siliceous sponges. The presence in the Beta member of chert nodules often formed around sponges, and the absence of these cherts in the Alpha, may be due to the difference in the depth at which the two members were deposited. Siliceous sponge spicules occur in the insoluble residue from locality 3, but whether they indicate a 'deeper water origin for the fossil-bearing rocks there is doubted, as other fossil forms closely resemble those from the other localities.

Several authors have related thickness and size of shells of mollusks and brachiopods to depth. Thickness of shells of the Kaibab fossils varies greatly, and lack of sufficient evidence one way or the other makes any generalization in this respect uncertain. It may be noted here that *Allorisma terminale* and *Aviculopecten kaibabensis* seem to have possessed thin shells relative to their size, while the shells of small forms such as *Astartella subquadrata*, *Palaeonucula levatiformis*, and *Manzanella cryptodentata*, in contrast, appear to be thick.

On a basis of the evidence here presented, it is thought that facies 3 and 4 of Kaibab Alpha, represented by the four zonules exam-

ined, were deposited at a depth not greater than 500 feet. If, as suggested below, the animals lived in a seaweed "forest," the depth must have been less than 100 feet.

BIOLOGICAL FACTORS: It is practically impossible to learn anything certain about the part played by biological factors in controlling a past fauna without direct evidence such as the presence of symbionts and parasites in their normal relationship, or the presence of scavengers and predators. Unfortunately, little such evidence is at hand in the Kaibab Alpha fauna.

The nature of the molluscan fauna, however, suggests the presence of a biological factor which may have been quite as important as depth and bottom conditions. Both pelecypods and gastropods are divisible into two groups: smooth-shelled, thick-shelled, often rather large forms; and light, finely ornamented, delicate shells. These two groups may have existed in the complex environment of a seaweed "forest," the finely ornamented, delicate forms clinging to seaweeds and the heavier, smooth-shelled forms burrowing and crawling in the mud beneath.

It is true that seaweeds grow on a hard bottom which facilitates anchorage of their holdfasts, but it is not inconceivable that, in quiet water, either algae or marine grasses may have been able to grow in the muddy bottom of epeiric Permian seas. There is no positive evidence of the existence of seaweeds, but the dual nature of the fauna suggests that they may have been present in abundance. The warm, shallow waters of the Kaibab seas must, of course, have offered an environment favorable to plant growth.

TEMPERATURE: The Kaibab sea was probably fairly shallow, as postulated above. Also the water was doubtless fairly quiet, as indicated below. At this latitude, assuming the climate to be similar to or warmer than that of today (as has generally been thought to be the case in the Northern Hemisphere during Permian time), a shallow, quiet sea would attain a temperature somewhat higher than that of seas of the same latitude today. Evidence that the climate was probably warm is given by gypsum deposits and associated red beds in both Toroweap and Kaibab formations, and by the presence of vast accumulations of eolian sands landward from these formations.

AGITATION: There is no evidence in the four fossil horizons of heavy wave or current action. The low proportion of land-derived clastic material in the limestones, particularly in that of bed 9 at Bottomless Pits, supports an hypothesis of the absence of pronounced agitation. The complete absence of ripple marks or cross-lamination in these beds does not serve as evidence, as finely particulate calcareous mud, particularly when held in position by shell fragments, would not support such features.

The delicacy of the spines of productids, as well as of the shells of many mollusks, is good evidence for moderately quiet waters. Many of the fossils are fragmentary, but this may be explained by the action of predators and the movement of other animals, and, without supporting evidence, should not be accredited to wave and current action. It has also been observed that fossil shells show evidence of stacking as though some rearranging of shells had taken place. This may have been caused by a slight amount of agitation on the bottom, by the action of burrowing animals pushing aside empty shells, or by disturbance of the water and bottom materials by action of scavengers or other animals of larger size. If seaweed "forests" sheltered the area, little strong wave action, except during periods of storm, is likely to have reached the bottom. It is thought, however, that slight agitation was present, at least periodically, and was strong enough to stir up the flocculent bottom muds.

There is present in the lower part of the Alpha member, as exposed in Walnut Canyon, one bed containing ripple marks. This bed extends over the entire area under discussion and represents a time of bottom conditions unlike those during the rest of Kaibab Alpha time. Strong agitation was present, but whether in the form of waves or currents is not ascertained.

Intraformational conglomerates at the top of the section indicate considerable current or wave action. This is as might be expected, for the increasing shallowness and nearness of the shore line as the sea retreated would permit

wave action more and more to reach the bottom.

TURBIDITY: From the sediments themselves, turbidity can be inferred only as a function of the rate of sedimentation. A study of insoluble residues is not sufficient to determine the amount of turbidity. The limestone appears to have been laid down as a fine calcareous mud, with a certain proportion of insoluble material. The presence of burrowing animals indicates that it remained fairly soft, at least in the uppermost few inches, and it is likely that a certain amount of flocculent mud on the surface of the bottom would cause considerable turbidity with the slightest agitation.

Evidence favoring this condition is given by the absence of corals and the almost entire absence of bryozoans. The lack of fusulinids and echinoderms may also have been caused by turbidity.

SALINITY: Salinity of water in epicontinental seas is basically a function of climate, though other factors, particularly currents or upwellings of water, may influence it.

It has been suggested that salinity of the Kaibab sea in the vicinity of Walnut Canyon was not "normal," but whether the water was brackish or highly saline was not determined (McKee, 1938, p. 137–139). Gypsum and red bed deposits in certain parts of the Alpha member suggest an arid climate that should have caused at least a periodic increase in salinity of the waters of the shallow seas. It is, however, within comprehension that the gypsum deposits were laid down in more or less isolated basins or lagoons while the seas represented by the Kaibab Alpha in the Walnut Canyon region and at locality 3 received abundant fresh waters from rivers and streams draining the adjacent land and so were brackish in nature. The presence of quartz grains may be due to introduction of material by streams, but could also be due in part or in whole to removal of sand and silt from beaches by waves or wind.

The nature of the fauna in many ways indicates that salinity may have been slightly below normal. The limited number of classes represented is in itself evidence that salinity was not normal, though turbidity may also be important in controlling animal types. The reduced size of the gastropods and pelecypods of the Kaibab has previously been interpreted as dwarfing due to low salinity, but on careful study the fauna appears not to be dwarfed, but rather to consist of an abundance of small forms, adapted to some special mode of life, with a high frequency of juveniles.

The presence of nautiloids in faunas lacking ammonoids is thought by Miller and Furnish (1937, p. 61) to indicate a difference in ecological requirements of the two groups, but whether the difference is one of salinity has not been demonstrated. Modern cephalopods are extremely sensitive to reduced salinity, and Paleozoic forms may well have been, also.

There is no paleogeographical evidence that the Alpha member of Kaibab was laid down in a basin isolated from the rest of the sea by a physical barrier, but it is probable that, lack of currents and other agitation contributing, there was a gradation in salinity from open sea to near-shore sea.

At several sections in the Alpha member, some beds contain faunas predominantly or entirely composed of one species, either *Schizodus texanus* or *Pleurophorus* cf. *P. mexicanus*. These faunas bear resemblance to modern occurrences of single, widespread species in regions of reduced salinity. They are euryhaline forms, able to withstand wide changes in salinity, and so exist in almost limitless abundance under conditions where their natural enemies are unable to live because of the rigors of the environment. It is probable that the *Pleurophorus* and *Schizodus* beds observed in Walnut Canyon, as well as those reported by McKee (1938, p. 143), represent periods of much reduced salinity, perhaps due to the shifting of the mouth of a river but more likely attributable to the development of off-shore bars preventing free circulation of the water.

CONCLUSION: The fauna of facies 3 and 4 of the Alpha member of the Kaibab formation, composed largely of mollusks but with brachiopods, trilobites, and bryozoa also represented, developed in a warm, shallow, epeiric sea of nearly normal or slightly reduced salinity, not very far from land. A gradual retreat of the sea was taking place, a fluctuating retreat probably only slightly modifying the depth of the sea. Agitation was at a minimum, but probably was sufficient to stir the flocculent muds

of the bottom. The land to the east was of low relief and the climate warm and possibly arid. Fine sands from the land were washed or blown into the sea in limited quantity only. It is likely that seaweeds grew in abundance, and that many of the small mollusks lived upon them, while others burrowed in the silty, clayey, calcareous mud of the bottom, mud composed primarily of fragmentary shells of dead organisms.

Systematic Paleontology

GASTROPODA

The gastropod fauna of the Kaibab Alpha differs markedly from any previously described fauna of the United States. It bears a strong similarity, however, to an as yet undescribed fauna from the Word limestone no. 1, and the two formations are thought to possess a number of species in common.

Of the 37 forms here discussed, 3 new genera and 22 new species are described. A chart of the relative abundance of gastropods in the collections from four faunules is presented in Table 1.

Abbreviations used in tables of measurements are as follows:

h = height
w = width
ha = height of aperture
wa = width of aperture
wh = number of whorls
mbw = minimum width of outermost whorl (in bellerophontids)
hbw = height of basal whorl
ϕ = pleural angle
aa = apical angle

Superfamily BELLEROPHONTACEA

Family BELLEROPHONTIDAE

Genus *Bellerophon* Montfort 1808

Bellerophon deflectus sp. nov.

Pl. 1, figs. 2a–5b

DESCRIPTION: Subglobose, spirally coiled, involute gastropods with width and height about equal, and with final whorl somewhat expanded. Whorls gently flattened on sides and top, strongly arched between, giving shell a subquadrate, shouldered cross-section; profile rising in median dorsal region to a rounded ridge bearing the selenizone; umbilici deep and narrow. Aperture broadly reniform; anterior lip convex between umbilici and selenizone in juveniles, becoming gently sinuous in early maturity and rather strongly so in adult shells, the sinus corre-

TABLE 1.—GASTROPODS, OCCURRENCE AND FREQUENCY CHART

	Loc. 1 bed 2	Loc. 1 bed 9	Loc. 2 bed 4	Loc. 3
Aclisina? bisulcata sp. nov.				xx
Ananias franciscanus sp. nov.				xx
Ananias gibber sp. nov.	x			
Bellerophon deflectus sp. nov.	x	x		xx
Eotrochus? liratus sp. nov.				x
Euconospira? cryptolirata sp. nov.	x			
Euomphalus kaibabensis sp. nov.	x			x
Euomphalus? sp. juvenile		x		
Euphemites aequisulcatus sp. nov.	x			xx
Euphemites sp.				x
Girtyspira? sp.		x		
Glabrocingulum? coronatum sp. nov.		x		x
Glabrocingulum laeviliratum sp. nov.	xx	xx		xxx
Glyptospira cristulata gen. et sp. nov.		x	?	xx
Goniasma? sp.		x		
cf. *Lepetopsis*	x	x		
Meekospira? sp. 1		x		
Meekospira? sp. 2		x		
Mourlonia? cancellata sp. nov.	x	x		
Murchisonia geminocarinata sp. nov.	x	xxx		x
Murchisonia sp.		x		
Naticopsis kaibabensis sp. nov.				xx
Naticopsis sp.	xx			
Oncochilus insolitus sp. nov.				x
Orthonema? striatonodosum sp. nov.		?		xx
Orthonema sp. 1				x
Orthonema? sp. 2		x		
Platyworthenia delicata gen. et sp. nov.				x
Retispira undulata sp. nov.	x		xxx	
Stegocoelia quadricostata sp. nov.	x			
Strianematina pulchrelirata gen. et sp. nov.	x			
Warthia sp.				x
Worthenia corrugata sp. nov.		x		x
Worthenia? sp.		x		
Genus et sp. indet. 1	x			

TABLE 1.—*Continued*

	Loc. 1 bed 2	Loc. 1 bed 9	Loc. 2 bed 4	Loc. 3
Genus et sp. indet. 2.....		x		xx

x—rare
xx—common
xxx—abundant

sponding with dorso-lateral shoulder of shell; median slit fairly deep, sharply defined in uneroded specimens; flare in lateral lip evident in early growth stages, well developed in adults and reflexed over umbilicus but not filling it; parietal inductura smooth but thick, nearly obscuring selenizonal ridge and forming a strong humped callus within the aperture of mature specimens.

Ornamentation absent; growth lines uneven in strength and usually clear; marginal lineation sharply defining selenizone; lunules arcuate, distinct, irregular in strength. Shell thick, especially in adults, reaching about 1 cm. in thickness in region of umbilicus in large specimens.

Width/height ratio gradually decreasing during ontogeny, so that young shells are as broad or broader than high while shells over 20 mm. in height are higher than broad. Shell increasingly thick with growth, especially in umbilical portions; parietal inductura becoming increasingly thick after shell reaches about 20 mm. diameter, becoming very prominent at about 60 mm.

MEASUREMENTS: 21 specimens were preserved well enough for measuring. Dimensions in mm.:

	h	w	ha	wa	mbw	w/h	ha/h
1.	76.5±	72.0	25.7	42.0	34±	.94	.34
2.	71.0±	67.0	26.5	42.0	34±	.94	.37
3.	67.6	59.1			30.0	.88	
4.		58.0			40±		
5.	63±	55.5			27±	.88	
6.	44.6	37.0	14.0	23.8		.83	
7.	42.0	43±	18±	30.5	24	1.02	.43
8.	38.0	36±	15.0	26.8	20.0	.95	.40
9.	29.2	28+	11.0	21.0	17.5	.96	.38
10.	21±	22±	7	14	11.8	1.05	.33
11.	18.7	16.0	9.0	15.0	10.1	.86	.48
12.	17.5	19±	6.5	15.0	10	1.09	.37
13.	17.0	16.0		17±	9±	.94	
14.	15.4	18.0±	5.5	11.7	10.7	1.17	.36
15.	13±	12.5			7.0	.96	
16.	13	13.5			5.5±	1.04	
17.	11.6	10	3.5±	7±	5.3	.86	.30
18.	10.0	10.0	3.5	7.7	5.2	1.00	.35
19.	9.0	7.0			3.8	.78	
20.	9.0	8.0	3.0	5.8	4.9	.89	.33
21.	6.8	7.0	2.0	4.7	4.1	1.03	.34

TYPES: Holotype: Mus. Northern Ariz. G2.472. Paratypes: Mus. Northern Ariz., Grand Canyon Nat. Park museum.

DISCUSSION: A series of growth stages, represented by the measurements above and by Figure 2, indicate that although great variation in size is shown, there is no sudden change dividing the series into two or more groups. The slow decrease in the

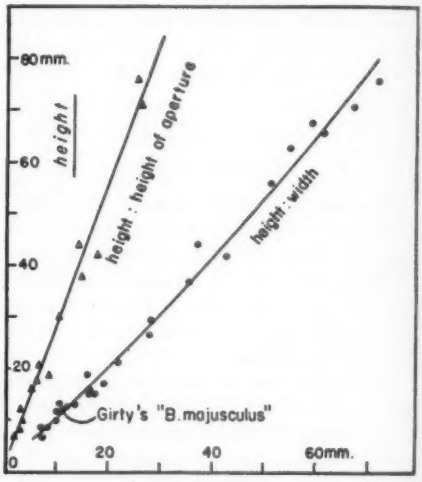

FIGURE 2.—RELATION OF WIDTH AND HEIGHT OF APERTURE TO HEIGHT IN *Bellerophon deflectus*

width/height ratio, the gradual development of the shoulder and its corresponding sinus in the lip, and the steadily increasing prominence of the parietal inductura show this to be an uninterrupted series representing a single species.

This form is not difficult to distinguish from other species of the genus *Bellerophon*, its shoulder flexure being diagnostic. Although it never attains the large size of Walcott's *B. majusculus*, it closely resembles that species but has a more elevated selenizone, a dorso-lateral shoulder, and a lip more widely flaring in the umbilical region. The thick parietal inductura diagnostic of *B. majusculus* is present here, but not so sharply delineated and seemingly thinner than in that form. In proportions a *Bellerophon* called *B. majusculus* by Girty (1909b), from the Yeso and San Andres formations, is like the Kaibab form. Although his figure shows a wider selenizone and does not show a strong shoulder angulation, it is possible that the two are conspecific.

B. blanfordianus Waagen, from the Productus limestone of the Salt Range, has a shoulder and a corresponding sinus, but appears not to have the thick parietal inductura developed in *B. deflectus*.

OCCURRENCE: Loc. 3 (common, silicified); loc. 1, beds 2, 9 (rare, fragmentary external molds).

Genus *Euphemites* Warthin 1930

Euphemites aequisulcatus sp. nov.

Pl. 1, figs. 1a–c

DESCRIPTION: Involute, spirally coiled gastropods of small to medium size, with whorls rapidly and regularly expanding. Whorls rounded rather evenly, though occasionally flattened along median line toward the aperture; umbilicus closed on either side by thickened corner of outer lip. Aperture transverse and flatly reniform, about same height at sides as in center; outer lip not preserved except at lateral margins, where it is thickened and produced into a decided flare; evidence of selenizone not apparent; parietal inductura extending over most of body whorl, marked with lirae.

Ornamentation 12–22 fine, irregular lirae on parietal inductura, closely and regularly spaced in center but not clearly marking position of selenizone; lirae fading out gradually so that last third of outer whorl is smooth; growth lines not visible.

MEASUREMENTS: Only four specimens were preserved well enough to permit measurement. These were broken around the outer lip. Dimensions in mm.:

	h	w	mbw	ha
1.	20±	20+	12	(holotype)
2.	13.8	14.8	7	4
3.	13.6	13+	7.2	3.5
4.	11.2	12	5	3

TYPES: Holotype: Mus. Northern Ariz. G2.1606. Paratypes: Mus. Northern Ariz., Amer. Mus. Nat. Hist., Grand Canyon Nat. Park museum.

DISCUSSION: This form bears a strong similarity to shells which have long been recognized as *E. carbonarius* (Cox), a species no longer considered valid (King, 1940, p. 151) as the type material is lost. Girty in describing "*E. carbonarius*" from the Wewoka formation suggests more variability and intermittency in the lirae than is evident in the specimens at hand, but it is likely that his forms are very similar to the Kaibab form.

The present form differs from Pennsylvanian species in its globose shape, the absence of an apertural callus or coinductural layer, and the absence of diagonal marginal lirae and nodes. Several Permian forms have been described which lack nodes or median carination, most of them differing from the present form in number and nature of lirae. *E. subpapillosus* (White), described from the Kaibab formation, is distinguished by the presence of papillae along the revolving carinae.

OCCURRENCE: Loc. 3 (common, silicified); loc. 1, bed 2 (rare, external molds).

Euphemites sp.

Pl. 2, fig. 2

A single crushed and somewhat fragmentary specimen of a large *Euphemites* differs from the preceding form by its much greater size and by the fact that each revolving lira is flat-topped and bears a minute furrow along its crest. Interspaces between lirae are shallow and flat-bottomed.

MEASUREMENTS: Width 40 mm. ±; height 40 mm. ±; height of aperture 14 mm.

DISCUSSION: No Permian species of *Euphemites* is known which shows flat-topped, furrowed lirae such as are seen in this form. The specimen at hand, while well enough preserved to show that it is distinctive, is partly imbedded in insoluble chertified limestone in such a manner that complete description is not possible.

OCCURRENCE: Loc. 3 (rare, silicified); the single specimen is at Grand Canyon Nat. Park museum, FK 704.

Genus *Retispira* KNIGHT 1945

Retispira undulata sp. nov.

Pl. 2, figs. 1a, b

DESCRIPTION: Involute, spirally coiled, globose gastropods of medium size, with whorls regularly expanding and not flaring at the aperture; height approximately equal to width. Whorls evenly rounded and without angulation at the selenizone; umbilical openings narrow and deep. Aperture reniform in cross-section; outer lip thin, with narrow sinus of moderate depth generating clearly defined selenizone flush with shell surface; posterior lip with thin, unornamented parietal inductura extending slightly out of aperture and completely covering ornamentation of previous whorl; inductural margin thin, concave and irregular; on the holotype, 3 small, low nodes, arranged in a triangular pattern, and an excentric ridgelike structure visible on one side of the inductura appear to be part of the inductural structure, but, as their occurrence can only be noted on that single specimen, their nature is not known for certainty.

Ornamentation of spiral lirae, spaced about 10 in 3 mm.; absent on selenizone; lirae varying in strength, every second or third being somewhat stronger than those between, probably because of increase in number of lirae by insertion; selenizone bounded by fine, sharp lirae, only locally visible and seemingly mostly eroded; under magnification 2 very obscure, fine lirae may be seen on selenizone, but these are usually obscured by erosion; transverse lirae forming narrow, arcuate undulations about 1 mm. apart, concave forward on each side

of selenizone and forming somewhat less well defined, undulate lunules on selenizone.

MEASUREMENTS: Of the few specimens available, all preserved as external molds, measurements could be made of only two. As far as can be judged by fragmentary specimens, the shape appears to be fairly constant, though the two specimens measured are among the smallest in the collection. The size range is more fully represented by consideration of a large, fragmentary specimen having a width of about 40 mm. The smallest shell identified with this species has an estimated height of 9 mm.

	w	h
1.	71.5±	18.0 (holotype)
2.	12.5±	14

TYPES: Holotype: Mus. Northern Ariz. G2.2959. Paratype: Mus. Northern Ariz. G2.2794.

DISCUSSION: Possession of a smooth parietal inductura and absence of a median internal carina distinguish this form from *Bucanopsis* and place it in the genus *Retispira*. The species is similar to *R. modesta* (Girty), being distinguished by its undulate transverse ornamentation and the selenizone flush with the shell surface. Also it is twice the size of Girty's shells. Still closer resemblance is shown with *R. textilis* (Hall).

The Kaibab shells have characters of juvenile Bellerophontids, in their globose shape and lack of the flaring lip typical of adults.

Undescribed collections at National Museum include forms from Word limestone no. 1 which may be adults of this form. They are much larger, with undulations more fully developed as their size increases. The larger fragments at hand from the Kaibab collections do not, however, show such pronounced development of undulations.

OCCURRENCE: Loc. 2, bed 4 (common, external molds).

Genus *Warthia* Waagen 1880

Warthia sp.

Pl. 2, figs. 3a–4

DESCRIPTION: Involute, spirally coiled gastropods of small to medium size, having a somewhat globose shape, and showing no evidence of a flare at the aperture. Whorls evenly rounded, most strongly curved at or near mid-line and flattening slightly on flanks; involution completely covering umbilicus. Aperture reniform in cross-section, more than twice as wide as high; outer lip with a median sinus of moderate width and depth, not producing a selenizone; parietal inductura absent.

Ornamentation lacking; growth lines cannot be seen.

MEASUREMENTS: Only four specimens were collected, all of them incomplete. Dimensions in mm.:

	h	w	ha
1.	20+	19.5	—
2.	18.1	16±	5.0
3.	15.5	14±	4±
4.	11.3	10.9	3.0

DISCUSSION: This form does not closely resemble any described American species of *Warthia*, although it has approximately the proportions of *W. brevisinuata* Waagen from the Salt Range. There is an undescribed form in the Word limestone no. 1 with similar proportions, but with a median ridge, absent on the Kaibab form.

Although these four specimens doubtless represent a new species, the fragmentary nature of the material does not permit an adequate characterization.

OCCURRENCE: Loc. 3 (rare, silicified).

Superfamily PLEUROTOMARIACEA

Family PLEUROTOMARIIDAE

Genus *Ananias* Knight 1945

Ananias franciscanus sp. nov.

Pl. 2, figs. 5a–6

DESCRIPTION: Small, moderately high-spired, turreted pleurotomarians of 6–8 or more gradually expanding whorls, with a pleural angle usually between 30° and 40°, lower in the most fully developed specimens. Suture slightly impressed, lying at or just below first basal costa; profile below suture sloping outward only very slightly to form a steep sigmoidal shoulder, convex above and concave below, to upper of 2 carinae; a strongly concave, fairly broad selenizone between 2 prominent carinae, the lower of which is peripheral; below periphery, flank is strongly concave, slightly wider than selenizone, and sloping inward to a poorly defined angulation limiting the base; base rounded, anomphalous or narrowly phaneromphalous. Aperture obliquely oval, its widest point near the middle; outer lip directed obliquely backward, with gentle sinuosity, from suture to selenizone, there forming a slit of probably only moderate depth; lip arching forward very slightly below selenizone, then becoming vertical across flank, and seemingly slightly concave between outermost few basal costae, but in general directed radially with slight

forward concavity across the base; columellar lip slightly flaring, reflexed; parietal inductura very thin at aperture, though thick enough further within whorl to conceal ornamentation of preceding whorl.

Ornamentation of revolving costae and lirae; shoulder with many fine lirae, 2 or 3 above center being more prominent than the others; 1 or 2 very fine lirae, often obscured, on selenizone; concave flank with 3 or 4 very fine lirae, often obscured, and with a single fine costa just above the regularly spaced basal costae; basal costae prominent, 7 or, more usually, 8 in number, becoming successively more closely spaced toward umbilicus, and separated by broad concave areas; growth lines fine but usually distinct; lunulae somewhat coarser than growth lines.

Nucleus of about 2 smooth whorls; selenizonal carinae appearing as first spiral ornamentation, followed almost simultaneously by most prominent of the shoulder lirae, flank costa, and most of basal costae; basal costae all forming during early development and then apparently remaining constant in number.

MEASUREMENTS: Fourteen well preserved specimens offer fairly complete dimensions (in mm.) of this form:

	h	w	ha	wa	w/h	ϕ	c	wh
1.	10.6	5.4	3.7	3.0	.51	33°	8	8+
2.	10.5	5.8	4.0	3.3	.55	34	8	7+
3.	10.3	5.5	3.9	3.0	.53	35	7	5½+
4.	9.2	4.9	3.2	2.4	.53	33	7	7+
5.	8.8	4.2	3.0		.48	26	8	6+
6.	8.5	5.1			.60	30		6+
7.	6.4	3.1			.48	34	8	5½+
8.	6.0	3.4	2.4	1.9	.57	42	7	7±
9.	5.2	3.1	2.0	1.7	.60	43	8	6+
10.	4.6	2.8	1.8	1.4	.61	41	8	7±
11.	4.2	2.6	1.7	1.5	.62			
12.	4.2	2.2	1.7		.52	38	7	6
13.	4.0	2.5			.62	40	8	
14.	2.2	1.4		.6	.64	42	7	5

c = number of basal costae

An increase in height relative to width, due to a change in pleural angle during ontogeny, is shown in Fig. 3.

TYPES: Holotype: Mus. Northern Ariz. G2.1595. Paratypes: Mus. Northern Ariz., Amer. Mus. Nat. Hist., Grand Canyon Nat. Park museum.

DISCUSSION: Although much more highly spired than other reported species of *Ananias*, this form bears such pronounced similarity with *A. whitei* Knight, to which it is undoubtedly related, that it cannot well be placed in any other genus. It possesses all the characters of the genus. *A. whitei*, first described and figured by White as *Pleurotomaria grayvillensis* Norwood and Pratten, was collected by Gilbert from the Kaibab limestone south of Pipe Springs, Arizona. It has a lower spire, and, to judge from White's figures, a somewhat differently

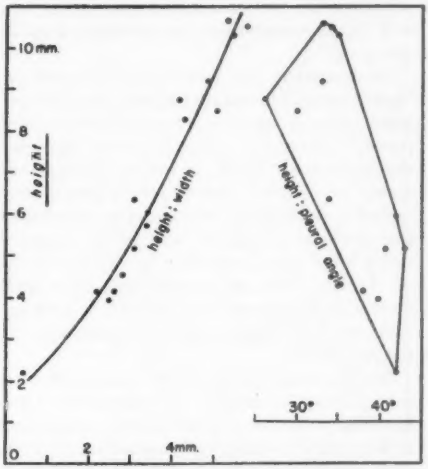

FIGURE 3.—RELATION OF WIDTH AND PLEURAL ANGLE TO HEIGHT IN *Ananias franciscanus*

placed selenizone than the present species, but striking similarity in its ornamentation makes relationship obvious.

No other described forms resemble *Ananias franciscanus*.

OCCURRENCE: Loc. 3 (common, silicified).

Ananias gibber sp. nov.

Pl. 2, fig. 10

DESCRIPTION: Shell of moderate size; whorls turbinate, turreted, regularly expanding. Suture strongly impressed; shoulder profile strongly sigmoidal in younger whorls, sharply convex just below suture and gently concave below this, flattening out as it approaches selenizone; convexity just below suture relatively reduced in last whorl; selenizone concave, bounded by fairly sharp carinae, the lower of which protrudes strongly below the upper; whorl profile concave immediately below selenizone and then becoming convex again, the convex portion protruding as far or farther than lower selenizonal carinae and forming periphery of shell; flank separated from base by an obscure angulation on lower portion of peripheral convexity; base seemingly flattened or gently convex; umbilical

region unknown. Outer lip directed backward with gentle sinuosity to selenizone; slit seemingly of moderate depth, with distinct lunules; lip directed forward immediately below selenizone, then almost straight, with very slight backward obliquity and forward convexity to lower obscure angulation, at which it arches backward and continues across base with forward concavity as far as visible; inner lip unknown.

Ornamentation fine, somewhat irregular revolving lirae on shoulder and sides, spaced about 0.1 mm. apart; every second or third lira stronger on convex portion of sides; liration much finer on base than elsewhere, and difficult to follow although the directional pattern is visible; growth lines distinct and often fasciculated, the bundles or crenulations thus produced tending to form radially elongated nodes below suture, especially in younger whorls; on the last whorl the crenulations become quite distinct on the shoulder and especially on sides and base, and form slight beads at intersections with revolving lirae.

Nucleus unknown; convexity below suture becoming less pronounced in last whorl, with corresponding reduction in radial nodes; crenulations resultant from reticulation of growth lines becoming more pronounced in last half of final whorl, especially on sides and base.

MEASUREMENTS: Only one specimen is known, an incomplete external mold. Measurements of it are in part estimated: height 11.5 mm. +; width 13.5 mm. ±; pleural angle about 90°.

TYPES: Holotype, an external mold of the final 3¼ whorls: Mus. Northern Ariz. G2.2968.

DISCUSSION: In general shape, the presence of carinae bounding the selenizone, and the fasciculate growth lines which form beading at intersections with revolving ornamentation, this form appears to belong to the genus *Ananias*. The lower carina bounding the selenizone protrudes well beyond the upper, however, so that the selenizone is more or less continuous in profile with the shoulder, while in the genotype of *Ananias* it protrudes only "very slightly." The pronounced bulging on the lower part of the whorl is not characteristic of other examples of the genus, nor is the strong sigmoidal curvature of the upper surface on all but the last whorl.

In shape and size this form is most nearly comparable to *A. welleri* (Newell) and *A. wannensis* (Newell), differing from both of these primarily in the sigmoidal profile of the shoulder and side. In ornamentation it is rather similar to *A. wannensis*, not possessing the pronounced beading shown by *A. welleri*. The spire of *A. welleri* is more strongly turreted than that of either *A. wannensis* or *A. gibbar*.

OCCURRENCE: Loc. 1, bed 2 (one external mold).

Genus *Euconospira* Ulrich 1897

Euconospira? cryptolirata sp. nov.

Pl. 2, figs. 11, 12

DESCRIPTION: Shell of moderate size, trochiform, of about 6 gradually enlarging volutions. Sutures shallow, impressed, lying at lower edge of selenizone in apical whorls, slightly below selenizone in adult whorls; profile of shoulder convex just below upper suture and concave from half way down shoulder to peripheral margin; periphery with a narrow selenizone bounded by lirae, the lower of which marks shell periphery; whorl profile below selenizone turning inward strongly, with an obscure angulation occurring some distance below periphery; base only slightly flattened, strongly convex toward umbilical region; umbilicus probably present, though nature of umbilical region is not fully known. Aperture incomplete; outer lip, as indicated by growth lines, leaving suture with a backward obliquity of about 50°, then curving with a still greater backward obliquity to a narrow slit which forms a selenizone in which growth lines are lunulate; lip projecting below selenizone with strong forward obliquity for a short distance, then arching backward, with strong forward convexity, toward umbilical region; inner lip unknown.

Ornamentation, low and somewhat obscure revolving carinae bordering selenizone; many faint revolving lirae on upper surface of whorl, spaced about 12 per mm.; revolving lirae of lower surface of same magnitude but less distinct; selenizone ornamented with finer spiral lirae, numbering about 15 where selenizone is 1 mm. in width; growth lines fine.

Ontogenetic variation is seen in position of suture, which lies in the first 3 whorls just on periphery of whorl above, and in later whorls slightly below periphery.

MEASUREMENTS: Only two specimens are known, both about the same size, and both incomplete. Measurements are approximations drawn from a study of both specimens (in mm.).

height	24±
width	19.5±
height of last whorl	12.7
height last whorl above periphery	6

TYPES: Syntypes: Mus. Northern Ariz. G2.545 and G2.547.

DISCUSSION: On the basis of its trochiform shape and the presence of a narrow selenizone just above the lower suture, this form is placed in the genus *Euconospira*. The base is considerably more convex than is usual for the genus, however, the measurement of the final whorl below the selenizone being about equal to that above. In this regard the form appears to be intermediate between *Euconospira* and *Mourlonia*. Astonishing similarity is shown to the Ordovician genus *Palaeoschisma* Donald.

The present species differs from *Euconospira obsoleta* Girty in its weaker growth lines, of equal strength on the upper and lower portions, in the faintness of its spiral ornamentation, and in the sigmoidal curve of its shoulder profile. It is similar to *E. turbiniformis* (Meek and Worthen), but has many more and finer revolving striae and a convex base.

OCCURRENCE: Loc. 1, bed 9 (two external molds).

Genus *Glabrocingulum* Thomas 1940

The genus *Glabrocingulum* differs little if at all from *Raphistomella* Kittl 1891, a Triassic form, and may be either identical with or ancestral to it. A complete analysis of the genotypes would be necessary to reveal relationships of the two genera.

Glabrocingulum laeviliratum sp. nov.

Pl. 2, figs. 7–9b

DESCRIPTION: Shell small, turbinate, composed of 4–6 whorls, usually somewhat wider than high but quite variable in this respect; spire moderately low; pleural angle generally of 90°–100° but varying widely. Whorl profile gently convex immediately below suture, then gently concave to periphery so that profile above periphery is sigmoidal; profile turning sharply vertical at periphery and having a broad, concave median band just below shoulder; strongly rounded below; base with moderately wide umbilicus; sutures well defined and lying usually just below median band of preceding whorl. Aperture almost circular, usually very slightly higher than wide, and slightly concave on upper, inner side; outer lip thin, with a slit generating a concave selenizone just above periphery of whorl; upper margin of lip directed backward as far as slit; below slit, lip curves gently backward to lowest part of whorl, where it is continuous with inner lip; inner lip narrow in young specimens, thickened and apparently reflexed slightly over umbilicus in more adult individuals.

Ornamentation fine revolving lirae, often indistinct above selenizone, usually quite distinct and fairly widely spaced below median band but more closely crowded toward base of whorl; lirae on base

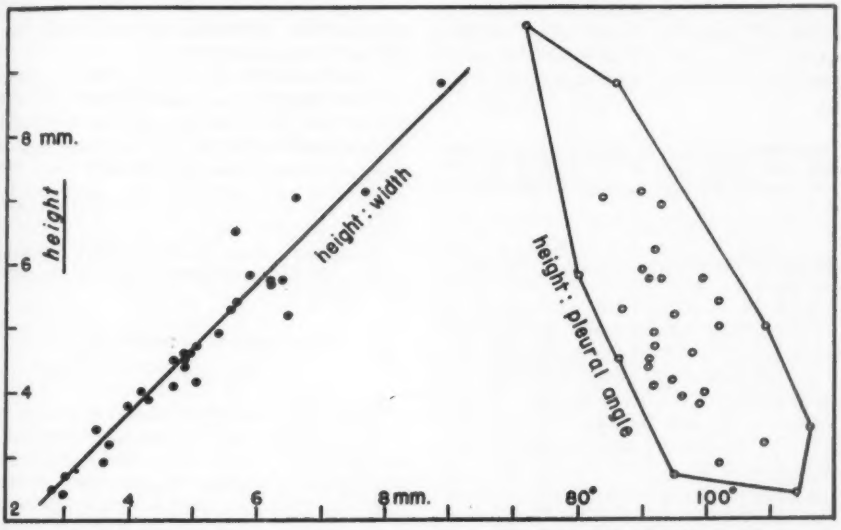

FIGURE 4.—RELATION OF WIDTH AND PLEURAL ANGLE TO HEIGHT IN *Glabrocingulum laeviliratum*

tending to form a cancellate pattern with growth lines, but not forming nodes; growth lines fine, directed sharply backward from suture to selenizone, gently concave forward across slit, then directed forward for a short distance below selenizone before continuing slightly backward to base of shell.

Protoconch about 0.1 mm. in diameter; first 2 whorls lacking ornamentation, next whorl bearing fine revolving lirae; angulation and selenizone appearing in fourth whorl; no perceptible change in proportion during growth (Fig. 4), although pleural angle tends to become smaller as shell increases in size.

MEASUREMENTS: An abundance of good specimens, with individuals of all stages of development, was on hand for measuring. Dimensions in mm.:

	h	w	ha	wa	h/w	ϕ	wh
1.	9.9	11.1					
2.	9.7		5.3	4.8		72°	
3.	8.8	8.9	5.1	4.6	.99	88	5¾
4.	7.1	7.7	4.6	4.2	.92	90	5
5.	7.0	6.6	4.1	3.5	1.06	84	
6.	6.9	7.7	4.7	3.8	.90	93	
7.	6.5	5.7±			1.14		5
8.	6.2	6.7	3.9	3.1	.93	92	5+
9.	5.9	6.5	3.9	3.7	.91	90	
10.	5.8	5.9	3.5	3.1	.98	80	4½
11.	5.7	6.4	4.0	3.4	.89	91	4¼
12.	5.7	6.2	3.7	3.2	.92	93	6
13.	5.7	6.2	3.8	3.8	.92	100	4¾
14.	5.4	5.7	3.9	3.2	.95	102	4½
15.	5.3	5.6	3.1	2.7	.95	87	4½
16.	5.2	6.5	3.8	3.2	.80	95	5¼
17.	5.0	5.9	3.5	3.0	.85	109	4¼
18.	4.9	5.4	3.1		.91	92	4¾
19.	4.7	5.1	3.0	2.8	.92	92	4¾
20.	4.6	5.0	3.1		.92		
21.	4.6	4.9	2.9	2.6	.94	98	5
22.	4.5	4.9	3.0	2.2	.92	86	4½
23.	4.5	4.7			.96	91	
24.	4.4	4.9	3.0	2.4	.90	91	4½
25.	4.3	4.9	2.9	2.9	.88	102	4¼
26.	4.2	5.1	2.9	2.7	.82	95	4
27.	4.1	4.7	2.5	2.3	.87	92	
28.	4.0	4.2	2.5	2.4	.95	100	5
29.	3.9	4.3	2.6	2.1	.91	96	4¼
30.	3.8	4.0	2.2	2.1	.95	99	4
31.	3.4	4.5	2.5	2.5	.76	116	4½
32.	3.2	3.7	2.0	2.0	.86	109	4
33.	2.9	3.6	1.9	1.8	.81	102	4
34.	2.7	3.0	1.8	1.5	.90	95	4
35.	2.5	2.8	1.8	1.6	.89		4
36.	2.4	3.0	2.0	1.8	.80	114	4

TYPES: Holotype: Mus. Northern Ariz. G2.567. Paratypes: Mus. Northern Ariz., Amer. Mus. Nat. Hist., Grand Canyon Nat. Park museum.

DISCUSSION: In general shape this species is closely similar to other species of *Glabrocingulum*; the lip and selenizone correspond with features of that genus, and nuclear characters of the genus are present. In details of ornamentation, however, this species does not agree with the original definition of *Glabrocingulum*, which includes nodose ornamentation on the basal portion, the spiral lirae forming tiny beads where they cross growth lines. As such fine details of ornamentation have usually been considered specific characters in gastropods, it is thought advisable here to consider the genus as including forms of similar shape which do not bear such nodose ornamentation.

G. laeviliratum may be related to Girty's species *"Baylea" euglyphea*, from which it differs primarily in its smaller size. It also has a sharper angulation at the shoulder than is shown in Girty's figure, and many specimens show the presence above the shoulder of very fine striae not mentioned by Girty.

OCCURRENCE: Loc. 1, bed 2 (rare, external molds), bed 9 (rare, external molds); loc. 3 (abundant, silicified).

Glabrocingulum? coronatum sp. nov.

Pl. 3, figs. 1a–3

DESCRIPTION: Low-spired, conical gastropods of about 5 gradually enlarging and rather deeply embracing whorls. Suture very slightly impressed; whorl profile below suture slightly sinuate, convex close to suture and concave toward marginal selenizone; selenizone located between 2 distinct carinae on shoulder angle; whorl somewhat concave, almost vertical but sloping gently outward below shoulder carina to a basal carina, at which it turns inward at an abrupt angle to form a gently convex, narrowly phaneromphalous base; umbilicus partly filled with a crescent-shaped callus, especially apparent in large specimens. Aperture roundly rectangular in cross-section, usually very slightly broader than high; outer lip thin above, slightly thickened near basal angulation; lip leaving suture at right angles, convex forward and directed backward with gentle obliquity to selenizone; shoulder angle with a narrow slit of, seemingly, considerable depth, generating a selenizone; below selenizone, outer lip slightly convex forward but directed almost vertically to lower angulation, whence it continues with a slightly arcuate pattern radially to umbilicus; columellar lip much thickened, presumably in formation of umbilical callus.

Ornamentation both radial and spiral; shoulder with fine arcuate growth lines developing near suture into radial undulations or elongate nodes giving surface a crown-like sculpture; shoulder surface with only very faint and fine spiral ornamentation, not evident on most specimens; selenizone

bounded by 2 sharp, angular spiral carinae; a less acute but no less distinct carina lying at the lower angulation; area between selenizone and lower carina with spiral ornamentation consisting of 4 or 5 rather unevenly spaced and somewhat irregular spiral lirae, crossed by fine arcuate growth lines; base with one very fine revolving lira immediately below lower carina, and with obscure growth lines.

Nucleus of 2 smooth, rounded whorls arising from a minute protoconch, projecting somewhat above the plane formed by flattened shoulders of later whorls; selenizone appearing at third whorl, followed quickly by appearance of coronal radial ornamentation. The suture often varies slightly in position during growth.

MEASUREMENTS: Five specimens were measurable, but two are external molds and did not permit complete measurement. Dimensions in mm.:

	h	w	ha	wa	ϕ	wh
1.	9.6	11.0			94°	6½
2.	4.5	5.6	2.4	2.5	108	5
3.	4.1	5.3	2.4	2.6	107	4¾
4.					112	5¼+ (mold)
5.		6.7			114	5+ (mold)

TYPES: Holotype: Mus. Northern Ariz. G2.554. Paratypes: Mus. Northern Ariz., Grand Canyon Nat. Park museum.

DISCUSSION: This form resembles representatives of the genus *Glabrocingulum* except for an angulation separating the base from the flank; typical specimens of *Glabrocingulum* are smoothly convex below the selenizone. In the angular whorl profile, specimens of *G.? coronatum* resemble *Worthenia*, but lack the diagnostic convex selenizone of that genus. No genus is known in which the lower angulation typically forms the shell periphery. A shell similar in general shape to *G.? coronatum* has been figured by Branson (1930, p. 56, pl. 99, figs. 14–16) under the name *Worthenopsis bicarinata*. It has the 2 carinae of this species, but the upper of the 2 forms the periphery of the shell. In addition, the shell is higher than wide while the Kaibab form is wider than high.

The sculpture and ornamentation of the upper surface seems nearly identical with that of *Glabrocingulum sarrauti* (Mansuy), but Mansuy's figures do not show a lower carina, and his description, as far as can be ascertained from a somewhat different terminology, does not include it. Spiral ornamentation of the upper surface is much fainter in the Kaibab specimens than in Mansuy's figures, the same being true in comparison with *G. grayvillense* (Norwood and Pratten), a species very similar to *G. sarrauti*.

Another form with similar ornamentation is a fragmentary specimen figured by Mansuy (1914, p. 39, pl. 7, fig. 5) as *Mourlonia?*. It bears ornamentation identical with that of *G.? coronatum* and may be closely related to or even conspecific with it.

An undescribed form from the Hueco formation of west Texas, now at the U. S. National Museum, appears to be exceedingly similar to this species.

OCCURRENCE: Loc. 1, bed 9 (rare, external molds); loc. 3 (rare, silicified).

Genus *Mourlonia* Koninck 1883

Mourlonia? cancellata sp. nov.

Pl. 3, figs. 4a–c

DESCRIPTION: Trochiform, somewhat globular gastropods of medium size with 6 or more rounded whorls increasing fairly rapidly in size. Sutures distinct, falling a short distance below selenizone; whorl gently rounded below suture as far as flattened peripheral selenizone, strongly arched at periphery; selenizone not quite vertical, sloping outward slightly toward its lower margin; base unknown. Apertural section unknown; upper lip convex forward and directed obliquely backward from suture to selenizone, forming a broad sinus culminating in a moderately wide slit which generates a selenizone on periphery of whorl; lip below selenizone convex forward and directed obliquely forward; basal portion of lip and inner lip unknown.

Ornamentation strong growth lines which become costa-like near upper suture, particularly in later whorls, the costae being rather sharply crested; radial ornamentation crossed by spiral lirae of about equal strength varying in number from 6 to 10, which in mature whorls occupy only lower part of shoulder, and which become less strong in final whorl; spiral lirae and radial ornamentation together forming a reticulate pattern but without well defined nodes; selenizone bounded by a pair of fine, high revolving lirae and sometimes bearing upon its surface an indistinct liration; lunulae indistinct, only slightly curved, sloping somewhat obliquely forward; ornamentation below selenizone seemingly similar to that above.

Nucleus of about 2½ smooth whorls; third whorl with both transverse and revolving ornamentation appearing at once, so that third and fourth whorls have entire surface covered by reticulate ornamentation; the following 1 or 2 whorls with only lower portion of shoulder thus ornamented, upper part covered by radial costae only; transverse ornamentation much reduced in last part of final whorl.

MEASUREMENTS: The three specimens at hand are external molds. Although squeezes were made from them they do not lend themselves well to measuring, as their bases are not preserved. Dimensions in mm.:

	w	height of spire
1.	12.5	7.5
2.	11.0	6.0
3.	9.5	5.2

TYPES: Holotype: Mus. Northern Ariz. G2.577. Paratype: Mus. Northern Ariz. G2.2985.

DISCUSSION: This form has the conical shape, rounded whorl profile, and peripheral selenizone of the genus *Mourlonia*, as well as spiral and radial ornamentation characteristic of many species of that genus. The basal and apertural characters cannot be seen, however. In size it is somewhat larger than many other species of *Mourlonia*. Similarity is noted between this form and the genus *Shansiella* Yin, characterized likewise by rounded whorls but with the selenizone located just below the periphery and without pronounced radial ornamentation.

Some resemblance may be seen between this form and Girty's *Mourlonia idahoensis*, from the Phosphoria formation of Idaho. The two differ, however, in the shape of the upper surface of the whorl, the profile in Girty's specimen appearing more strongly arched. The base is not preserved in the Kaibab forms so comparison in that respect is not possible. Spiral ornamentation is more marked in the present form, though revolving grooves defining the selenizone in Girty's specimens are not present here.

The shape is similar to that of *M. nana* Yin, from Permian beds in China, but that species has cancellate ornamentation of fine growth lines upon more fully developed lirae.

OCCURRENCE: Loc. 1, beds 2 and 9 (rare, external molds).

Genus *Pernotrochus* gen. nov.

DEFINITION: Turbinate gastropods of moderate size having a more or less flattened shoulder and a flat base becoming convex near periphery and meeting shoulder at a well defined angulation; outer lip with a v-shaped sinus seemingly terminating on final whorl in a shallow slit which forms a poorly defined selenizone with indistinct lunulae; ornamentation fine revolving lirae; base with a funnel-like umbilicus bounded by an obtuse angulation.

GENOTYPE: *Pernotrochus arizonensis* sp. nov.

DISCUSSION: The establishment of a new genus on two external molds, one of the base and one of the spire, is undertaken with an appreciation of the assumptions made and of the risks involved. The very excellent preservation of the specimens, which enables clear and distinct rubber squeezes to be made, allows no doubt that the form is new, and the close similarity of ornamentation on both specimens indicates that they represent the same species. A steinkern that was attached to the external mold of the spire shows configuration of the base similar to that of the external mold of the base. Observations on the peripheral angulation, part of which was preserved in both specimens, and on the general size and shape of the specimens likewise indicates their relationship. The two specimens occur close to each other, almost touching in fact, both on a single sample of rock.

The exact relationships of this genus are difficult to determine since the absence of a selenizone in the first several whorls is unusual. Assuming a selenizone to be present in late stages, however, the genus shows relationship to *Euconospira* in its flattened upper whorl surface and in the angulation bounding the umbilicus, but has neither the sharp peripheral carinae nor the very flat base characteristic of that genus.

Distinct changes in the location of the suture and in the calibre of the ornamentation during growth are noted in the genotype, but may be characters of no more than specific rank. Only by discovery of more specimens and species may it be ascertained whether these changes are a consistent feature of the genus.

RANGE: Permian, Kaibab formation.

Pernotrochus arizonensis sp. nov.

Pl. 3, figs. 5a–7

DESCRIPTION: Trochiform gastropods of moderate size, consisting of 6 or more whorls regularly increasing in size. Suture distinct, impressed, lying slightly below peripheral angulation on first 4 whorls, then coming to lie on peripheral angle so that shell is cone-shaped; upper surface of whorl very gently convex in upper half and concave in lower half, producing a slightly sigmoidal profile inclined at an angle of about 40° to the axis; in final whorl, a broad flat area lies between upper convex and lower concave portions, the concave part becoming a well defined, narrow band seemingly representing a selenizone; periphery angular and abrupt, with a slight carina formed by concavity of upper surface; base very gently rounded, flat toward umbilicus, with an obtuse angulation

marking the limits of a funnel-like umbilicus. Aperture quadrate in cross-section (by reconstruction), its margin directed obliquely backward, with forward convexity, from suture across most of whorl face, and then arching, in last 2 whorls at least, to cross periphery in a forwardly direction, forming a poorly defined concave sinus or slit; this slit in the last whorl forming a selenizone; lip continuing to be directed forward for a short distance on the base, then arching abruptly to a radial direction continuous to umbilicus; columellar lip reflexed sharply toward umbilicus, parietal lip unknown.

Ornamentation fine spiral lirae, spaced about 16–20 per mm. on base, distributed over entire surface including selenizone; spiral lirae on more youthful whorls fewer in number, more widely spaced (10 per mm.), and not continuing quite to periphery; new lirae introduced by intercalation; growth lines fine, and usually obscure near peripheral portion of upper surface.

Nucleus of 2 smooth whorls, followed by 2½ whorls in which spiral lirae are coarsely spaced and periphery of shell projects slightly over lower suture; later whorls with finer liration and with periphery covered by succeeding whorl. In first 5 whorls there is no trace of a selenizone, though in the last whorl there is one, poorly defined possibly because of the shallowness of the slit and indistinctness of the lunulae.

MEASUREMENTS: Only two specimens are known, one of the base and the other of the spire. Measurements are approximations drawn from a study of both specimens: height of spire above periphery of last whorl 8.0 mm.; depth of base below periphery of last whorl 2.0 mm.; estimated total height 10.0 mm.; width 11.0 mm.

TYPES: Syntypes: Mus. Northern Ariz. G2.1305.

OCCURRENCE: Loc. 1, bed? (very rare, external molds).

Genus *Platyworthenia* gen. nov.

DEFINITION: Small, turreted pleurotomarians having a flat shoulder, flat, vertical flank, and a flattened anomphalous base separated from each other by sharp carinae; outer lip with a sinus terminating at upper carina in a convex selenizone; ornamentation revolving lirae and carinae; nucleus of several smooth whorls planospirally coiled.

GENOTYPE: *Platyworthenia delicata* sp. nov.

DISCUSSION: This genus shows striking resemblance to the genus *Platypleurotomaria* Wanner, which, like it, has a planospirally coiled nucleus. But Wanner's form has a concave selenizone, whereas the selenizone of the present form is, like that of *Worthenia*, convex and straddling the upper carina.

RANGE: Permian, Kaibab formation.

Platyworthenia delicata sp. nov.

Pl. 3, figs. 8a–9

DESCRIPTION: Very small, turreted pleurotomarians of about 4 or 5 regularly enlarging volutions. Suture located on basal angulation of preceding whorl; shoulder profile flat except for a slight rise near center, sloping outward below suture at an angle of about 40° to axis of shell; profile becoming abruptly vertical at prominent upper carina and forming a flank of about the same breadth as the shoulder; base flattened, anomphalous, delineated from flank by a sharp carinated angulation. Aperture almost circular; outer lip directed obliquely backward from suture to a shallow notch which straddles upper angulation, giving rise to an angularly convex selenizone; lip directed gently forward below selenizone to second flank lira, below which it becomes directed almost vertically or with gentle backward obliquity to lower carina; lip almost radial on base; columellar lip thickened and reflexed; parietal inductura probably present.

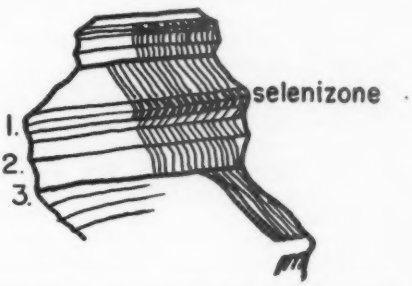

FIGURE 5.—POSITION OF CARINAE AND SELENIZONE IN *Platyworthenia delicata*

Ornamentation prominent spiral lirae and carinae of varying strength; shoulder without visible liration except for the sharp but fine upper boundary of selenizone; lower selenizonal lira, on flank, sharp and fine; flank with 3 equally prominent carinae, the upper one bearing the selenizone, not noded but showing distinct lunulae, the second one at about the middle of the flank, and the third at basal angulation; between selenizone and second carina is a fine liration at which outer lip turns downward; base with 4 or 5 regular, evenly spaced, strong lirae.

Nucleus of about 2 smooth whorls planospirally coiled; the 3 flank carinae appear simultaneously on the third whorl.

MEASUREMENTS: Two specimens are known from loc. 3 which are well enough preserved for complete measuring. A third doubtful specimen, from loc. 2, bed 4, is somewhat larger. Dimensions in mm.:

	h	w	ha	wa	hbw	ϕ
1.	5.5+	4.8				52°
2.	4.5	3.2	2.0	1.8	3.2	51
3.	3.9	3.0	1.8	1.6	2.8	50 (holotype)

TYPES: Holotype: Mus. Northern Ariz. G2.571. Paratype: Amer. Mus. Nat. Hist.

DISCUSSION: The two specimens from loc. 3 differ from the dubious specimen from loc. 2, bed 4, in that they are smaller in size and have much more prominent ornamentation. The third specimen, however, shows the convex selenizone and flattened nucleus characteristic of the genus, and is weakly lirated to correspond with the carination of specimens from loc. 1. The difference in ornamentation and size may be an ecological one, or the ornamentation may have been reduced by erosion.

OCCURRENCE: Loc. 3 (rare, silicified); loc. 2, bed 4 (very rare, external mold).

Genus *Worthenia* de Koninck 1883

Worthenia corrugata sp. nov.

Pl. 4, figs. 1a–c

DESCRIPTION: Small turbinate gastropods of about 5 whorls, with spire medium in height; suture impressed, lying just at base of vertical side of whorl; whorl profile slightly flattened above, sloping outward at 55° to axis, turning abruptly vertical at shoulder angle, and inward below a vertical face at an obscure angulation; base rounded; umbilicus narrow. Aperture not quite circular; outer lip thin, directed backward in a sigmoidal curve on the shoulder to a slit above the center generating a convex selenizone on shoulder angle; lip below selenizone directed obliquely forward at first, then arching to a backward obliquity on the base; outer lip continuous with columellar lip, which is reflexed slightly over umbilicus; parietal inductura seemingly absent.

Ornamentation consisting of 13 strong revolving carinae, 2 located on shoulder, a third forming shoulder angle, fourth and fifth on vertical side of shell, and next 8, more closely spaced than the preceding and becoming slightly more crowded toward umbilicus, occupying lower rounded portion of whorl; between second and third carinae, and also between third and fourth, there are small sharp lirae defining selenizone margins, the third or shoulder carina thus running through selenizone

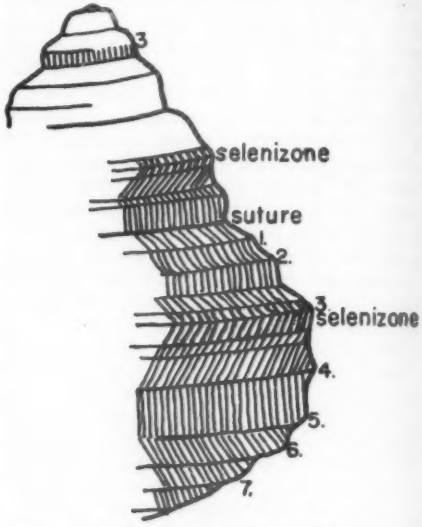

FIGURE 6.—POSITION OF CARINAE AND SELENIZONE IN *Worthenia corrugata*

slightly above its center; lower bounding lira of selenizone with another equally fine or finer lira immediately below it. Growth lines usually distinct; lunules in selenizone very evenly spaced and regular, but not forming the strong nodes usually characteristic of the genus.

Nucleus small, the first 1½ whorls without ornamentation; third carina appears first, then fourth, fifth, second, and first, in that order.

MEASUREMENTS: Only two specimens were preserved well enough for measuring. Dimensions in mm.:

	h	w	ha	wa	w/h	ϕ
1.	7.0	5.8	3.7	3.4	.83	65.5°
2.	4.1	3.9	2.5	2.1	.95	80

TYPES: Holotype: Amer. Mus. Nat. Hist. 27109:1. Paratypes: Amer. Mus. Nat. Hist. and Mus. Northern Ariz.

DISCUSSION: The position of the selenizone straddling the shoulder angle, and the enlargement of the lunules in the selenizone, place this form in the genus *Worthenia*. In shape, ornamentation, and

size, it appears extremely similar to Girty's *Baylea texana*, and may easily be mistaken for it, although according to his description the selenizone of that form lies between lirae 3 and 4 while in the excellently preserved specimens from the Kaibab it clearly straddles the third lira. Wanner's *Pleurotomaria minima* is rather similar in configuration but has the slit-band between whorls 2 and 3. Comparison of the Kaibab specimens with his figure makes it difficult to believe that the two are not the same, although according to his description *P. minima* has but 12 lirae while *W. corrugata* has 13. *Cyclonema bitauniensis* Wanner is in some ways also similar, but is several times as large and is defined as having 15 lirae and no selenizone. Wanner observed a fine lira between lirae 3 and 4 which corresponds to the lower boundary of the selenizone of the Kaibab form. Discovery and examination of better material may prove that *C. bitauniensis* is a *Worthenia* closely related to *W. corrugata*.

A form similar to this, but considerably larger in size, from the Word limestone no. 1 of the type locality in Texas, is thought to be the same species, but it may be that the Kaibab individuals are juveniles or are dwarfed due to ecologic conditions.

OCCURRENCE: Loc. 3 (rare, silicified); loc. 1, bed 9 (rare, external molds).

Worthenia? sp.

Pl. 5, fig. 9

Several external molds of a small gastropod of unknown affinities are too poorly preserved to be named or described. They resemble *Worthenia*, in which genus they are tentively placed, but show only spiral ornamentation on the upper and lateral surfaces. The base is not preserved. Although growth lines cannot be seen, there is a suggestion of a selenizone lying across the shoulder angle. The shoulder is decidedly sigmoidal in profile, the flank nearly vertical. The nucleus consists of 2½ smooth, rounded whorls.

OCCURRENCE: Loc. 1, bed 9 (rare, external molds).

Family MURCHISONIIDAE

Genus ***Goniasma*** Tomlin 1930

Goniasma? sp.

Pl. 4, fig. 9

DESCRIPTION: High-spired, many whorled gastropods of medium size. Suture not impressed but well defined, located some distance below the carina on earliest few whorls, immediately below it on last 5 or more whorls; shoulder profile concave and inclined outward to a low, rounded carina which seems to bear a selenizone; base seemingly almost flat. Aperture unknown; outer lip almost straight, gently oblique backwards almost to carina and then becoming strongly oblique backwards to carina; selenizone seemingly narrow and located on carina; lip seemingly directed very sharply forward on base; inner lip unknown.

Ornamentation faint nodes on the carina and faint spiral lirae covering the entire shoulder surface; 2 fine lirae present on base, just below carina and about 1 mm. farther in. Growth lines faint and fine.

MEASUREMENTS: Only one specimen is well enough preserved to permit measurements of the shell. It has the following dimensions: height 37 mm., width 13.8 mm., number of whorls 10+.

To facilitate comparison with *Murchisonia?* sp. and *M. geminocarinata*, measurements of the position of the selenizone on various whorls of the two fragmentary specimens are represented graphically in Figure 8.

DISCUSSION: In the nodose selenizone and in the proportions of its uppermost few whorls, this form resembles *Murchisonia geminocarinata*. In its stronger spiral ornamentation however it shows more affinity to *M. terebra* White. The proportions of the later whorls and position of the carina immediately above the lower suture are similar to *Murchisonia* sp. 1. Yet in its seemingly flattened base it cannot be likened to any of those species. Poorness of preservation and lack of complete specimens make it impossible to do more than record this form here.

OCCURRENCE: Loc. 1, bed 9 (very rare, external molds).

Genus ***Murchisonia*** Archaic and Verneuil 1841

Murchisonia geminocarinata sp. nov.

Pl. 4, figs. 12–14

DESCRIPTION: High-spired, turreted gastropods of small to moderate size, with 5 to 10 or more whorls depending on stage of growth. Suture shallow but clear; whorl profile straight just below suture, sloping out at 20° from axis, concave in lower half of shoulder to shoulder angle, which is occupied by a projecting carina marking position of selenizone; carina varying in position but generally about two-thirds of distance down from upper suture to lower; below carina, profile turning sharply inward, almost perpendicular to shoulder, and continuing with slight concavity to an angulation lying almost on line of suture; below this, the basal profile again

turning inward to a second angulation, below which it is concave and curves downward into a rudimentary anterior canal. Aperture irregularly triangular in cross section; outer lip directed backward below suture, continuing with slight forward convexity to a peripheral slit of unknown depth, forming a selenizone in peripheral carina; below slit, lip directed obliquely forward, convex, running in an arc to anterior canal; columellar lip seemingly rotated inward to form a border to the canal; parietal portion of inner lip unknown.

Ornamentation consisting of a row of nodes along selenizone, apparent only in ephebic whorls; revolving lirae on shoulder and between peripheral carina and sub-sutural angulation very fine and often obliterated; base with several very low rounded lirae, the uppermost of which lies at the subsutural angulation; growth lines very fine.

Nucleus of about 6 whorls with selenizone bordered by a pair of sharp carinae, and without evidence of nodes; at about the sixth whorl, carinae become slightly and separately noded, the nodes merging gradually until there is but a single row of them and the carina appears single and rounded.

MEASUREMENTS: Since the tip of the spire is nearly always broken, measurements of height usually must be approximated. Dimensions in mm.:

	h	w	h/w	ϕ	wh
1.	27.0	10.5	.40	24°	11+
2.	25	11.8	.47	25	9
3.	25+	9.0	.36	26	10+
4.	23				8+
5.	16+	7	.43	24	6+
6.	15+	6.6	.44	28	
7.	15+	6.5	.43	23	7+
8.	15	6.2	.41		7+
9.	12.5	5.0	.40	24	6+
10.	11+	3.9+	.35	24	10+
11.	10+	4.7	.47	20	7+
12.	9.2+	3.7	.40	26	8+
13.	7.6	3.3	.43	23½	8

There is no apparent regular change in pleural angle or proportions during growth (Fig. 7).

TYPES: Holotype: Mus. Northern Ariz. G2.353. Paratypes: Mus. Northern Ariz. and Grand Canyon Nat. Park museum.

DISCUSSION: This form bears a strong resemblance to *Murchisonia terebra*, described and illustrated by White from south of Pipe Springs, probably from the Kaibab formation. That form, however, bears strong revolving ornamentation and has nodes only very weakly developed; examination of the type shows that it is not the same as this form. In general it may be said that specimens recorded as *M. terebra* by White (1883), Keyes (1894), and Girty (1909) are too poorly described and illustrated to identify with either species.

Knight observed (1940) that in *Murchisonia gouldii* the position of the selenizone on the whorl varies considerably not only between specimens but between the whorls of a single specimen. This is also true of *M. geminocarinata*. Measurements of the height of the whorls between sutures and of the distance between the upper suture and the center of the selenizone were made on 63 whorls on 13 specimens. The ratio between height of whorl and distance from suture to selenizone was calculated, giving a numerical figure for position of the selenizone ranging from .50 to .76, with an average of .63. The ratios show a curve of normal distribution. Figure 8 shows that although the range in some individuals is very large, in others it is rather small and there is only slight variation in the regularity of the whorls..

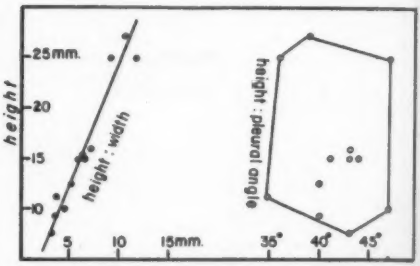

FIGURE 7.—RELATION OF WIDTH AND PLEURAL ANGLE TO HEIGHT IN *Murchisonia geminocarinata*

The nature of the selenizone on early whorls and its development during the ontogeny of the shell is readily observed and is of special interest since, in different stages, there is resemblance to the selenizone of other species. In the juvenile whorls, the sharply carinated selenizone is reminiscent of *Murchisonia gouldii*. From about the sixth whorl from the apex, the 2 carinae, each with gradually developing elongate nodes, bear strong resemblance to the doubly nodular carina of *Helicospira buttersi* (Girty) from the Lykins formation of Colorado, although the shell lacks the pronounced transverse ornamentation of *Helicospira*. This stage may be termed the neanic stage of the shell. The ephebic or adult stage is arrived at slowly by a merging of the nodes of the 2 carinae and a consequent obscuring of the exact boundaries of the selenizone.

OCCURRENCE: Loc. 1, bed 2 (rare, external molds), bed 9 (common, external molds); loc. 3 (rare, silicified).

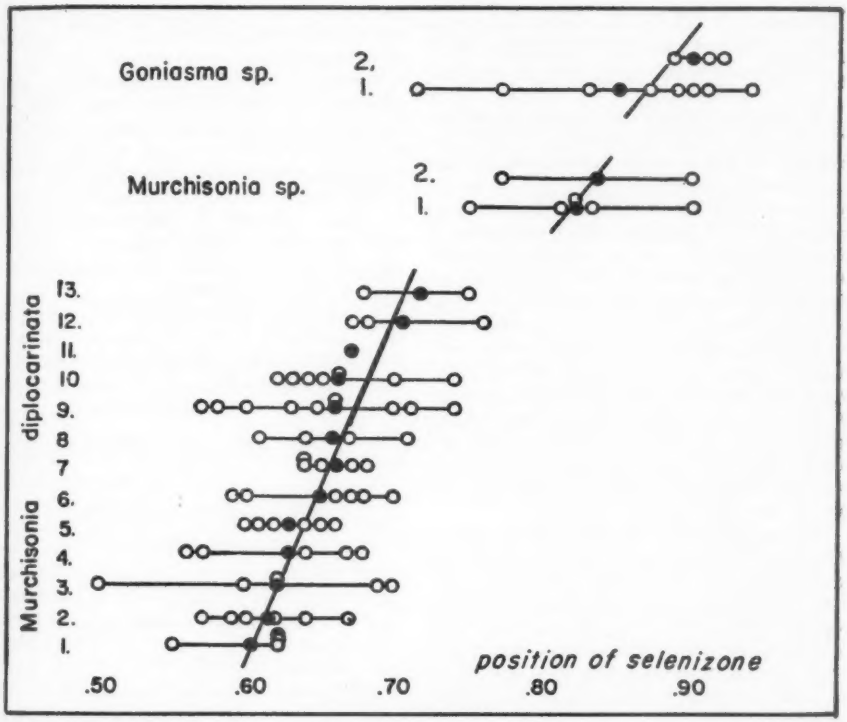

FIGURE 8.—POSITION OF SELENIZONE IN *Murchisonia geminocarinata*, *Murchisonia* sp., and *Goniasma* sp.

Murchisonia sp.

Pl. 4, fig. 11

DESCRIPTION: Medium-sized, high-spired, many whorled gastropods. Suture slightly impressed, clearly defined, lying just below peripheral angulation; shoulder profile sigmoidal, sloping vertically or even a little inward below the suture, then curving outward to periphery of whorl; profile turning abruptly inward below the narrowly rounded periphery, and curving inward and downward for a short distance to an obscure angulation limiting the flattened base; umbilical portion of base unknown. Aperture unknown; upper lip seemingly straight and oblique backwards from suture to periphery, which may be occupied by a selenizone; lip below periphery apparently directed sharply and obliquely forward, at least to the obscure basal angulation, beyond which its course is unknown; inner lip unknown.

Ornamentation, except for indistinct nodes along selenizone, absent or not in evidence; very faint growth lines have been observed.

MEASUREMENTS: A squeeze from a poorly preserved external mold shows the following dimensions: height 30 mm. +; width 14.5 mm.; number of whorls 7.

A second fragment, probably of the same species, reaches a diameter of about 43 mm., and the entire shell must originally have measured at least 12 or 15 cm. in height.

DISCUSSION: The material at hand is too poor to be identified accurately or described completely, but examination of the fragmentary specimens shows them to have the selenizone lower than in Knight's specimens of *M. gouldii* or in specimens of *M. geminocarinata* sp. nov. (Fig. 8), and to have a sigmoidal shoulder pattern not characteristic of those species. In addition, the pleural angle is greater, resulting in a greater width/height ratio. This form lacks the spiral ornamentation characteristic of *M. terebra* but may be an eroded specimen of that species.

OCCURRENCE: Loc. 1, bed 9 (rare, external molds).

Genus ***Stegocoelia*** Donald 1889

Stegocoelia quadricostata sp. nov.

Pl. 4, fig. 10

DESCRIPTION: Minute, high-spired, somewhat turreted shells with a very low pleural angle so that the sides are almost parallel in adult whorls; number of whorls unknown but more than 6; whorls only very slowly expanding. Whorl profile sloping sharply outward from the rather deep suture to first of 4 carinae, then almost vertically downward to third carina, below third, sloping inward to fourth; base defined by a sharp angulation at lowest carina, and incompletely known but probably flattened; suture lying just below fourth carina. Aperture unknown; outer lip almost vertical below suture to first carina, then oblique backward to second carina and forming a slit of unknown depth giving rise to a selenizone between second and third; lunulae very gently concave; lip directed obliquely forward below selenizone; columellar and parietal lips unknown.

Ornamentation consisting of 4 revolving carinae, the distance between suture and first carina and between first and second carinae about half that between second and third, and that between third and fourth about two-thirds that between second and third; first and third carinae the most prominent, forming respectively the upper and lower limits of the vertical side of the whorl; growth lines very fine.

MEASUREMENTS: Only one specimen, the holotype, is known. It reveals neither the base nor the tip of the spire. Measurements of a rubber squeeze are as follows: length 5.9 mm.; width 1.8 mm.; pleural angle 11°.

TYPES: Holotype: Mus. Northern Ariz. G2.2983.

DISCUSSION: Although not all of the characters of the genus are revealed in this specimen, the nature of the outer lip, known from the growth lines, shows it to be a Murchisonid. It bears close resemblance to members of the genus *Stegocoelia*, although the position of the selenizone is considerably lower on the whorl face than in other species. The general shape, with very slowly expanding whorls showing a low pleural angle, and the nature of the spiral ornamentation, is in agreement with that genus. The predominance of the first and third lirae cause a flattening of the side of the whorl which contrasts with the more rounded whorls of other members of the genus. The nature of the columellar lip, important in the diagnosis of the genus, cannot be seen on the specimen.

This species bears strong resemblance to the Mississippian "*Murchisonia*" *attenuata*, "*M.*" *vermicula*, and "*M.*" *turritella*, Hall, forms which are not mutually distinguishable and which are probably conspecific.

Superficial resemblance is seen to *S. cincta* (Donald), and to the type of the genus, *S. compacta* Donald, the primary difference being in the number, position, and relative strength of the revolving costae and in the position of the selenizone. There is also strong resemblance to a number of species of *Orthonema*, especially *O. marvinwelleri* Knight, which has however a different spacing of the lirae and is thought to lack a selenizone, although growth lines and lip are not preserved.

No other forms have been described which bear close resemblance to the new species, although a form almost identical with it has been observed in the U. S. National Museum collections from the Word limestone no. 1 at its type locality.

OCCURRENCE: Loc. 1, bed 2 (very rare, external mold).

Superfamily EUOMPHALACEA

Family EUOMPHALIDAE

Genus ***Euomphalus*** Sowerby 1814

Euomphalus kaibabensis sp. nov.

Pl. 4, figs. 15-16c

DESCRIPTION: Discoidal, planospirally coiled gastropods of about 4 volutions, the whorls increasing fairly rapidly in size but without covering upper and lower surfaces of preceding whorls. Whorl profile angular, with upper and lower carinae giving shell a trapezoidal cross-section; upper suture sharp and in an angulation formed by upper surface of whorl with side of previous whorl, which projects somewhat above suture; upper surface gently convex near suture, flat or very gently concave in remaining part; upper carina sharp and nodose; outer surface fairly convex and sometimes tending to have a faint angulation midway between upper and lower carinae; lower carina more rounded than upper and bearing a row of prominent rounded nodes; base of whorls rounded so that lower sutures are fairly deep; umbilicus broad, its sides forming an angle of about 90°. Upper lip directed perpendicularly outward from suture, seemingly curving backward to form a shallow sinus on upper carina, and then curving forward and vertically downward on outside of whorl, more or less radially but with slight forward concavity on basal surface; aperture subtrapezoidal to subpentagonal in shape. Ornamentation consisting of elongate nodes on both upper and lower carinae, these numbering 10 in the last volution of a specimen 31 mm. in diameter; growth lines

fine and much eroded from specimens at hand; spiral ornamentation lacking.

MEASUREMENTS: Of the 4 specimens at hand only 1 is complete. Partial measurements of the others give an idea of the size range. Dimensions in mm.:

	d	wa	h	ha
1.	30.8	12.2	12.2	12.0 (holotype)
2.	22.8	9±		
3.		14.5	14.5	14.0
4.		7.3		8.4

TYPES: Holotype: Mus. Northern Ariz. G2.557. Paratype: Mus. Northern Ariz. G2.547.

DISCUSSION: The presence of an upper sharp carina and a lower more rounded one, both projecting about equally, places this form in the genus *Euomphalus* rather than in *Amphiscapha*, although the nodose character of the carinae at first suggests assignment to the latter.

A strong resemblance may be seen between *E. kaibabensis* and the Pennsylvanian *E. pernodosus* Meek and Worthen. The form differs, however, in its smaller size and in the possession of well-defined nodes on the upper carina. Illustrations of *E. pernodosus* by Meek and Worthen show the upper carina as relatively smooth and the texts of their papers describe it as rugose or somewhat corrugated. The nodes on *E. kaibabensis* are as distinct even on somewhat eroded specimens on the upper as on the lower carinae, and are about equal in number, often occupying alternating positions.

Another markedly similar form is *E. nodocarinatus* Wanner, which differs in its less rapidly expanding whorls, which give it a wider umbilicus and a lesser height in proportion to its diameter. It also has a more convex outer surface than the Kaibab form, with resultant lesser angularity in the whorl profile.

This appears to be a long-ranging species, and has been observed by the author in collections of the U. S. National Museum from the Word limestone no. 1 and from the San Andres, as well as in collections from the Fort Apache limestone of Arizona, now at the American Museum of Natural History.

OCCURRENCE: Loc. 1, bed 2 (very rare, external molds); loc. 3 (rare, silicified).

Euomphalus? sp., juvenile

Pl. 4, fig. 2

An external mold of the base of a small spiral gastropod reveals characteristics seen in the juveniles of the genus *Euomphalus*, many of which possess angular upper and lower carinae in youthful stages. Apparently subquadrate in cross-section, it cannot however be assigned to the genus *Amphiscapha* as the lower carina projects downward rather than outward as in that genus.

OCCURRENCE: Loc. 1, bed 9 (very rare, external mold).

Superfamily PATELLACEA

Family PATELLIDAE

Genus *Lepetopsis* Whitfield 1882

cf. *Lepetopsis*

Pl. 4, figs. 3a, b

External and internal molds of a small, low-coned patellid, and an internal mold of a somewhat larger specimen, do not show enough characters to be accurately classified. Their measurements are recorded here, however, and the form is figured. They probably represent a new species.

MEASUREMENTS: (in mm):

	l	w	h
1.	12.0	9.5	3.8 (internal mold)
2.	5.3	3.8	2.0 (external mold)

OCCURRENCE: Loc. 1, beds 2 and 9 (very rare, external and internal molds).

Superfamily TROCHONEMATACEA

Family TROCHONEMATIDAE

Genus *Glyptospira* gen. nov.

DEFINITION: Small, moderately high-spired, turbinate gastropods with rounded aperture, gently oblique outer lip, and no slit or selenizone; whorls rounded or slightly angular, sutures deep; anomphalous or minutely phaneromphalous. Ornamentation prominent revolving carinae, varying in number and strength, on sides and base; growth lines usually distinct. Nuclear whorls smooth.

GENOTYPE: *Glyptospira cristulata* sp. nov.

DISCUSSION: This genus bears little resemblance to any other Paleozoic genus except *Microdoma* Meek and Worthen, from which it may be descended. It may be in line of descent through *Microdoma* from the genus *Pagodea* Perner. Species of the genus have been observed in the Wolfcampian (Hueco limestone), Leonardian (Bone Springs formation), and Guadalupian (Word lime-

stone no. 1) of Texas, in the collections of the U. S. National Museum, but have not been described. They were discussed by J. B. Knight at the Novem-

lira; umbilicus very minute or not apparent. Aperture almost circular, very slightly flattened at base and somewhat pointed at suture; outer lip thin,

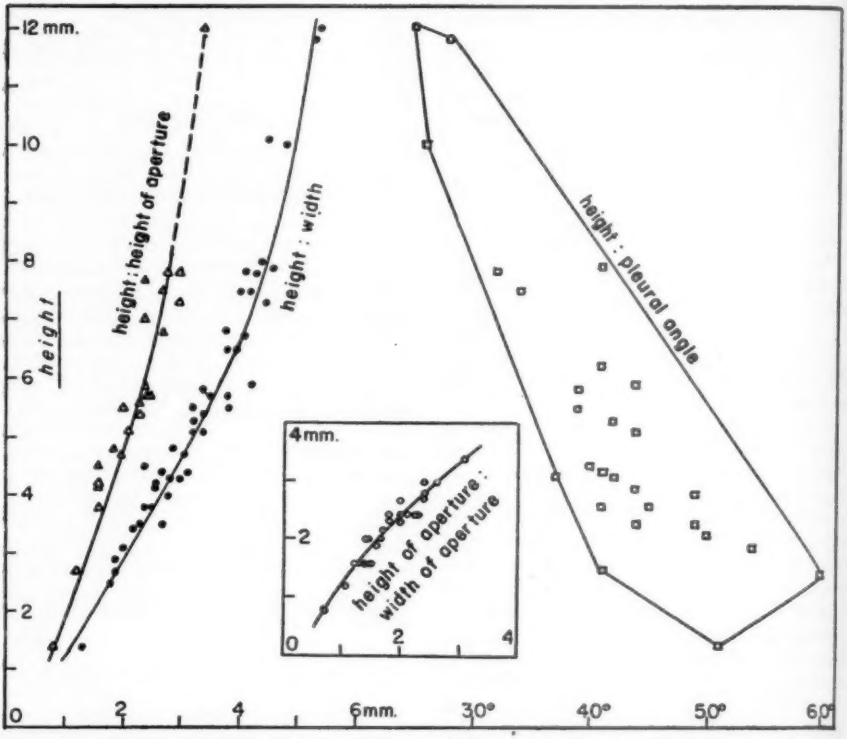

FIGURE 9.—RELATION OF WIDTH, PLEURAL ANGLE, AND HEIGHT OF APERTURE TO HEIGHT, AND OF HEIGHT OF APERTURE TO WIDTH OF APERTURE, IN *Glyptospira cristulata*

ber 1948 Geological Society of America meetings in New York. Variation in proportion, number of carinae or lirae, and degree of prominence of ornamentation may be considered specific and subspecific characters.

RANGE: Permian.

Glyptospira cristulata sp. nov.

Pl. 4, figs. 4a–6b

DESCRIPTION: Small gastropods with moderately high spire and 5–8 whorls, with a pleural angle ranging from about 50° in juveniles to about 25° in largest specimens. Whorl profile rounded, most convex just below periphery of shell and becoming less convex toward base; sutures moderately deep, impressed, and lying just below fourth revolving locally thickened as it meets spiral ornamentation, and directed with gentle backward obliquity and forward convexity from suture to umbilical region; no slit, notch, or selenizone is present.

Ornamentation 3 strong, rounded, revolving carinae on flanks and 5 or 6 less prominent lirae on base; the first of the carinae lying a short distance below suture, second and third forming periphery of whorl; first lira lies at or immediately above lower suture; lirae becoming successively broader and less pronounced toward base, until the last is barely visible; growth lines fine and very sharply raised.

Nucleus of 2½ smooth whorls, with ornamentation appearing on third whorl; second and third carinae appear first and for several whorls remain the most prominent. There is a distinct change in proportions during growth, the smallest individuals having a width/height ratio of about 0.90, and the

largest having a ratio of about 0.45. The change in proportions is accompanied by a decrease in pleural angle from about 50° to about 25°, and possibly by a slight change in shape of aperture.

MEASUREMENTS: An abundance of specimens was available for measuring, representing all growth stages. Dimensions in mm.:

	h	w	ha	wa	w/h	ϕ	wh
1.	12±	5.4	3.4	3.1	.45	25°	6±
2.	10.8	5.3			.49	28	
3.	10.1±	4.5			.45		7½
4.	10.0±	4.8±			.48	26	
5.	8.0+	4.4			.55		
6.	7.9	4.6			.58	41	
7.	7.8	4.1	3.0	2.4	.53		8
8.	7.8	4.3	2.8	2.4	.55		6¾
9.	7.5	4.2	2.7	2.2	.56		
10.	7.5	4.0			.53	34	
11.	7.3	4.5	3.0	2.6	.62		6
12.	6.8	3.8	2.7	2.0	.56	41	7½
13.	6.7	4.1	2.4	2.1	.61		6
14.	6.5	3.8	2.4	2.1	.58		5½
15.	5.9	4.2			.71	44	
16.	5.8	3.9			.67		6
17.	5.8	3.4	2.4	2.0	.59	39	6
18.	5.7	3.5	2.4	1.8	.61		6
19.	5.7	3.8	2.4	2.1	.67		
20.	5.6	3.5	2.4	2.0	.62		5½
21.	5.5	3.8			.69		
22.	5.5	3.2	2.0	1.7	.58	39	6
23.	5.4	3.4	2.3	1.8	.63		7½
24.	5.3	3.2			.60	42	
25.	5.1	3.2			.63	44	
26.	5.1	3.4	2.1	1.7	.67		
27.	4.8	3.1	2.0	1.5	.66		5½
28.	4.7	3.1	2.0	1.5	.66		5½
29.	4.5	2.4	1.6	1.5	.53	40	5½
30.	4.4	3.1	2.0	1.5	.70	41	5+
31.	4.4	2.7			.61	41	
32.	4.3	2.6		1.6	.65	42	
33.	4.3	3.0			.70	37	
34.	4.2	2.5	1.6	1.3	.62		6
35.	4.1	2.6	1.6	1.3	.63	44	6¼
36.	4.0	2.8			.70	49	
37.	3.8	2.5			.66	41	
38.	3.8	2.4	1.6	1.4	.63	45	5½
39.	3.5	2.7			.77	49	
40.	3.5	2.4			.66	44	5½
41.	3.4	2.2			.65	50	
42.	3.1	2.0			.65	54	
43.	2.9	1.9			.66		
44.	2.7	1.9	1.2	1.1	.70	41	
45.	2.6	1.9			.73	60	
46.	1.4	1.3	0.8	0.7	.93	51	4

Changes in proportion and in pleural angle with growth are represented in Figure 9.

TYPES: Holotype: Amer. Mus. Nat. Hist. 27108:1. Paratypes: Amer. Mus. Nat. Hist., Mus. Northern Ariz., Grand Canyon Nat. Park museum.

OCCURRENCE: Loc. 1, bed 9 (very rare, external molds); loc. 2, bed 4 (very rare, external molds); loc. 3 (abundant, silicified).

Family PALAEONUSTIDAE

Genus *Eotrochus* Whitfield 1882

Eotrochus? liratus sp. nov.

Pl. 4, figs. 7a–8

DESCRIPTION: Shell conical, twice as wide as high, with a pleural angle of about about 100°; 4–5 volutions enlarging regularly; suture appressed, each whorl overlapping preceding one slightly, forming a narrow step at suture. Whorl profile very slightly convex below this for about ⅔ distance down whorl, then very slightly concave to shoulder angle, but in general appearing almost flat and sloping strongly outward; lamellar extension of shoulder slope extending downward and outward about .3 mm. below base, forming a flange; base, surrounded by flange, flat near outer margin, then rounded regularly into umbilicus. Aperture lens-shaped in cross-section, somewhat less convex on upper side than below, and rounded at outer margin by a thickening of calcareous material. Upper lip leaving suture almost at right angles, then curving obliquely posteriorly in a broad arc until at periphery of shell it is almost parallel to margin; lower lip, as indicated by faint growth lines, very slightly oblique forward on outer flat portion of base, then becoming almost radial as it crosses third, or largest, of basal lirae; growth lines cannot be traced on lower surface of flange; parietal inductura lacking.

Ornamentation 6 or 7 fine, evenly spaced, revolving lirae of equal magnitude on shoulder slope; 5 stronger revolving lirae on base of shell, the first lying close to flange, the second in center of flat area of base, the third and strongest forming boundary between outer flat area and that part of shell which arches into umbilicus, the fourth and fifth, which are successively less strong, lying on umbilical portion; a sixth lira sometimes present, but usually only vaguely suggested; growth lines faint.

Nuclear whorls seemingly no different in shape than later whorls, lacking visible ornamentation; first certain appearance of lirae on third whorl below apex.

MEASUREMENTS: (in mm.):

	h	w	ha	wa	hbw	ϕ	h/w
1.	3.8	7.6	1.6	2.6	2.0	92°	.50 (holo-
2.	3.3	6.0		2.5	1.9	96	.55 type)
3.	3.0	5.4	1.3	3.0	1.6	107	.55

TYPES: Holotype: Amer. Mus. Nat. Hist. 27111:1. Paratypes: Amer. Mus. Nat. Hist., Mus. Northern Ariz.

DISCUSSION: This form has been assigned to the genus *Eotrochus* on the basis of its shape and size,

the shape of the aperture, the presence of a peripheral flange, and the shape and sculpture of the base, as well as on the presence of spiral lirae and lack of radial ornamentation. The upward extension of the columellar lip seen by Knight (1932) in sectioning a paratype of the genus, is not present in these specimens, however. If the extension of the lip is to be considered a generic character, this form represents a new genus.

There is also resemblance to *Flemingella* Knight, but that genus lacks the basal flange and is very narrowly phaneromphalous. In addition, its spire is not usually as low as in *Eotrochus*.

The course of the lower lip, which could not be seen on the genotype, can be seen on *E.? liratus*.

In its smaller size, presence of revolving lirae on the shoulder slope, and ornamentation of the base, this shell differs from *E. tenuimarginatus* (Miller). The latter has a smooth upper surface and a large number of fine revolving lirae on the lower surface, and appears to have a smaller pleural angle than *E.? liratus*.

OCCURRENCE: Loc. 3 (rare, silicified).

Superfamily TROCHACEA

Family TROCHOTURBINIDAE

Genus *Strianematina* gen. nov.

DEFINITION: Moderately high-spired, sub-turbinate gastropods having a thin, nearly straight outer lip directed with slight backward obliquity and probably having a simple inner lip and a thin parietal inductura. The genus is characterized by fine revolving striae on the base, and, in some species, near the upper suture.

GENOTYPE: *Strianematina pulchrelirata* sp. nov.

DISCUSSION: *Strianematina* shows close relationship to the genus *Strophostylus* Hall, and, more particularly, to *Anematina* Knight, differing from both of these in the presence of revolving ornamentation. In his definition of *Anematina*, Knight (1933, p. 36) parenthetically broadened the definition to include the occasional presence of revolving ornamentation on the base, as in *A. marshalli* (Roundy), a species which now is embraced by *Strianematina*. Thus the genus *Anematina* may be restricted to forms completely lacking ornamentation.

RANGE: Mississippian to Permian.

Strianematina pulchrelirata sp. nov.

Pl. 5, fig. 3

DESCRIPTION: Moderately high-spired, sub-turbinate gastropods with at least 6 whorls and with a pleural angle of approximately 39°; final whorl measuring about two-thirds entire height of spire. Suture slightly impressed; whorl profile gently rounded, somewhat more strongly rounded below suture and between flank and base, the whole blending into a smooth curve; base rounded, probably minutely phaneromphalous. Aperture seemingly oval, rounded below and somewhat pointed above; outer lip thin, nearly straight, and gently oblique backwards, rounding below and seemingly continuous with inner lip; inner lip unknown, parietal inductura apparently absent, thin, or not extensive.

Ornamentation fine revolving striae, spaced about 9 or 10 per mm. on base; on last whorl, about 5 revolving striae similar to those on base may be seen just below suture; growth lines fine. Nucleus unknown.

MEASUREMENTS: The spire of the single specimen is not complete so that shell height is estimated. Height 17 mm. ±; width 8 mm.; height of aperture 7.5 mm.; width of aperture 4.9 mm.

TYPES: Holotype: Mus. Northern Ariz. G2.2735.

DISCUSSION: The species is based on only one specimen, an external mold revealing clearly the characteristic ornamentation.

OCCURRENCE: Loc. 1, bed 2 (very rare, external mold).

Superfamily SUBULITACEA

Family PSEUDOMELANIIDAE

Genus *Girtyspira* Knight 1936

Girtyspira? sp.

Pl. 5, fig. 1

Two small external molds revealing some of the characteristics of the genus *Girtyspira* are tentatively placed with that genus. Their rounded whorl profile with narrow angular shoulder just below the suture, their sub-conical base, and reflexed inductura, as well as the absence of ornamentation, tend to place them in this genus, although the specimens are too poorly preserved to make assignment certain.

OCCURRENCE: Loc. 1, bed 9 (rare, external molds).

Genus *Meekospira* Ulrich 1897

Meekospira? sp. 1

Pl. 5, fig. 2

DESCRIPTION: High-spired, many whorled gastropods with a low apical angle and a somewhat higher pleural angle; whorls gradually expanding, with height of final whorl measuring slightly more than half the height of entire shell. Suture impressed, fairly deep; whorl rounded below suture, somewhat flatter on sides; base with a rudimentary anterior canal. Apertural section somewhat pointed below, more sharply pointed above, and widest below middle, showing in young specimens an increase in convexity between side and base of shell; outer lip thin and probably almost straight or gently convex forward; columellar lip unknown; parietal inductura passing out of sight into the aperture.

Ornamentation 4 fine, regularly spaced striae on outer basal portion of whorl; growth lines barely visible. Nucleus unknown.

MEASUREMENTS: Only one specimen, an external mold of which rubber squeezes were made, was collected. Its dimensions are: height 16.2 mm.; width 5.0 mm.; height of aperture 5.5 mm.; width of aperture 2.8 mm.; pleural angle 15°; width/height ratio .31.

DISCUSSION: The whorl shape and the nature of the parietal inductura are the only bases for placing this form in the genus *Meekospira*, a genus which normally shows no spiral ornamentation of any kind. Though this form may represent a new genus, material at hand is not adequate for complete description and definition.

OCCURRENCE: Loc. 1, bed 9 (rare, external molds).

Meekospira? sp. 2

Pl. 5, fig. 4

DESCRIPTION: High-spired, many whorled gastropods with a high pleural angle and with height of final whorl less than a third the height of the shell. Suture impressed; whorl profile rounded below suture, somewhat flatter on sides, especially in early whorls, so that an obscure shoulder is formed; another strongly rounded region below flank divides flank from base; final whorl evenly rounded and somewhat more bulbous in shape; base with, possibly, an anterior canal. Outer lip thin, straight on neanic whorls, concave forward on later whorls and becoming convex forward very near columella, suggesting an anterior canal; columellar lip almost vertical; parietal inductura smooth and with its upper margin arching back into aperture and disappearing long before reaching suture.

Spiral ornamentation absent; growth lines fine but distinct. Nucleus unknown.

MEASUREMENTS: Several external molds were collected, most of them too fragmentary for measuring. One specimen was fairly complete except for the tip of the spire. Height 18.2 mm. +; width 5.7 mm.; height of aperture 5.7 mm.; width of aperture 2.4 mm.; pleural angle 19°+; width/height ratio .32.

DISCUSSION: On a basis of the character of the parietal inductura this form is tentatively grouped with *Meekospira*. The shape of the whorls and their proportions are not, however, completely typical of that genus and this form may well belong in some other genus, possibly *Pseudozygopleura* Knight, although without the diagnostic nuclear whorls that assignment cannot be made, or in *Acteonina*, which typically has a well developed, narrow shoulder below the suture.

The change in shape of the whorl in this species, marking the end of the neanic and the beginning of the adult stage, is quite distinctive, accompanied as it is by a change in the shape of the outer lip. The change in profile causes a sudden difference in the pleural angle, which may be as much as 23° if measured from a rounded whorl to a flatter one, or as low as 15° if measured on 2 succeeding flattened whorls of a young specimen.

Several Pennsylvanian species of *Meekospira* show superficial similarity to the Kaibab form, among them *M. peracuta* (Meek and Worthen), which, however, does not show the rounding and expansion of the final whorl so characteristic of the present species.

OCCURRENCE: Loc. 1, bed 9 (rare, external molds).

Family SUBULITIDAE

Genus *Onchochilus* Pethö 1882

The Permian genus *Cylindritopsis*, named by Gemmellaro in 1890 to include forms having a double fold on the callus-like parietal lip, seems to be synonymous with the Triassic genus *Oncochilus* Pethö. The genus *Naticodon* Ryckholt is also in many ways like members of the genera *Cylindritopsis* and *Oncochilus*. That genus, however, was never adequately described, and cannot be recognized.

Oncochilus has priority and is here used as the name of a Permian species which, though higher-spired than many previously described species, shows the double fold clearly.

Oncochilus insolitus sp. nov.

Pl. 5, fig. 7

DESCRIPTION: Minute, roundly fusiform gastropods with about 5 rapidly expanding volutions, each deeply embracing preceding one so that the spire projects above body whorl a distance equal to only about a fourth the length of body whorl. Suture only slightly depressed; whorl profile smoothly rounded below suture, straightening slightly near pointed base; anomphalous. Aperture semicircular, measuring more than half the height of shell, slightly rounded at base, coming to a point at upper end; outer lip thin, slightly convex forward, describing an arc downward and backward and straightening as it approaches siphonal notch; siphonal notch rounded and bounded above by a well developed siphonal fold; parietal inductura thickened, extending as a callus beyond aperture, and developed into a siphonal fold at lower end and into a parietal fold of approximately the same size, located half the distance up parietal side of aperture.

Shell smooth; growth lines not visible.

Nuclear whorls apparently of same shape as later whorls; parietal fold seemingly not strongly developed in youthful whorls but forming a low angulation that lends strong resemblance to the genus *Strobeus*; parietal fold attaining a size almost equal to that of siphonal fold by fifth whorl.

MEASUREMENTS: Two specimens were excellently preserved and permitted complete measurements to be made. Dimensions in mm.:

	h	w	ha	wa	hbw	w/h
1.	5.1	3.4	2.8	1.6	4.0	.67 (holotype)
2.	4.0	2.6	2.4	1.3	3.1	.65

TYPES: Holotype: Amer. Mus. Nat. Hist. 27113:1. Paratype: Mus. Northern Ariz.

DISCUSSION: This form differs from Triassic species of *Oncochilus* in its higher spire and more fusiform shape. It is smaller in size and somewhat more globose than Gemmellaro's species "*Cylindritopsis*" *ovalis* and "*C.*" *inflatus*. "*C.*" *minimus*, "*C.*" *cheilodontus*, and "*C.*" *conicus*, Gemmellaro's other species, are probably conspecific and differ from the present form in their more elongate shape, greater proportionate height of final whorl, and nature of lip. Except for "*C.*" *minimus*, which was probably a juvenile, they are larger than the Kaibab form.

Undescribed specimens in the U. S. National Museum, collected from Word Limestone no. 1 of the Glass Mountains, Texas, are very like *Oncochilus insolitus*. Closely related forms are also in collections from the Texas Hueco and Leonard formations.

OCCURRENCE: Loc. 3 (very rare, silicified).

Superfamily SUBULITACEA?

Family STREPTACIDIDAE?

Genus ***Aclisina*** de Koninck 1882

Aclisina? bisulcata sp. nov.

Pl. 5, figs. 5a–6

DESCRIPTION: Small, moderately high-spired gastropods of approximately 6 regularly expanding volutions and with a pleural angle generally between 30° and 40°. Suture slightly impressed, located on or just below the lowermost of 3 low but distinct lirae on flank; profile below suture only very slightly convex, becoming flat almost immediately to form a steep flank rounding gradually below into a slightly flattened base; base very minutely phaneromphalous. Aperture somewhat rectangular, pointed at suture; outer lip thin, gently oblique backwards with slight forward convexity to periphery, and with slight forward concavity on base; columellar lip thin, vertical, reflexed; parietal inductura lacking.

Ornamentation 3 low, rounded revolving lirae dividing flank from base, separated by 2 broad, shallow depressions; the lowermost of the 3 lirae is actually the first of 12–16 fine basal lirae, which become finer and more closely spaced toward umbilicus; flank with a suggestion of very fine liration; growth lines obscure.

Nucleus of 2 or 3 smooth whorls, the first of which is coiled almost in a plane; spiral grooves between peripheral lirae appear first, followed by lirae.

MEASUREMENTS: Of 12 measureable specimens, several were partially broken around aperture or tip of spire. Dimensions in mm.:

	h	w	ha	wa	w/h	ϕ	s	wh
1.	9.4	4.2	3.4	2.3	.45	32	12	6½
2.	9.0	4.0	3.2+		.43	29		7
3.	8.6	4.1			.48	32	16	7+
4.	6.1	3.2			.53	31	14+	6
5.	5.9	3.1	1.7	1.5	.53	33	15	6+
6.	5.8	3.3	2.1	1.7	.57	29	13	6
7.	5.6	3.2	2.3	1.7	.57	36	15	6
8.	5.3+	2.9	1.8+	1.5	.55	37		6+
9.	5.0	2.9	1.6		.58	33		5+
10.	4.1	2.4	1.6	1.3	.59	40	14	5
11.		2.4	1.7	1.2			14	
12.	3.5	2.0	1.3	1.1	.57	28	13+	5

s = number of basal striae.

TYPES: Holotype: Amer. Mus. Nat. Hist. 27116:1. Paratypes: Amer. Mus. Nat. Hist., Mus. Northern Ariz., Grand Canyon Nat. Park museum.

DISCUSSION: Because of poorness of preservation, of growth lines in particular, this form cannot be well assigned generically. In nature of ornamentation it seems to be closest to the genus *Aclisina*, although it does not show the sinuate lip nor the inductural characters of that genus. In addition, the nucleus appears planospiral and not, as is frequent in *Aclisina*, detached, and the spire is lower and the whorls more flattened than in that genus.

No closely similar species is known.

OCCURRENCE: Loc. 3 (common, silicified).

Family PSEUDOMELANIIDAE?

Genius et species indet. 1

Pl. 5, fig. 8

A fragmentary external mold of 2 whorls of a small gastropod could not be identified. It is finely and delicately ornamented with alternating strong and weak spiral lirae, and shows straight growth lines only very gently oblique backwards, suggesting that it may belong to the family Pseudomelaniidae. It shows resemblance to the Triassic genus *Rhabdoconcha*, but is not completely enough preserved to assign generically.

OCCURRENCE: Loc. 1, bed 2 (very rare, external mold).

Superfamily NERITACEA

Family NERITOPSIDAE

Genus *Naticopsis* McCoy 1844

Naticopsis kaibabensis sp. nov.

Pl. 5, figs. 10a–11b

DESCRIPTION: Small, globose, very low-spired gastropods varying in proportion from slightly higher than wide to slightly wider than high; 3–4 rapidly enlarging volutions, each embracing almost the whole of preceding whorl; spire projecting less than 1 mm. above final whorl. Whorl profile inflated, with broad, gently convex upper and lateral surfaces sometimes showing a slight development of a shoulder, and becoming straight on base; anomphalous. Aperture tear-drop shaped, widest at or very slightly below center; length of aperture about 0.8 or 0.9 that of shell; outer lip directed backward from suture at an angle of about 80°, and running obliquely backward with forward convexity to basal portion of shell, then almost radially; parietal lip thickened, with a callus-like inductura extending outside of aperture and sharply flattened near columella.

Surfaced marked by fine growth lines, without other ornamentation.

Nucleus similar to later whorls, there being no evidence of any regular change in proportions during ontogeny (Fig. 10).

MEASUREMENTS: A fairly large number of specimens were available, covering a good range in size and representing all ontogenetic stages. Dimensions in mm.:

	h	w	ha	wa	w/h	ha/h	wh
1.	11.0	10.2	9.0	6.3	.93	.82	4
2.	10.6	10.2	9.6	6.7	.83	.91	3¾
3.	9.9	10.3	8.9	5.4	1.04	.90	3¾
4.	9.1	8.5	7.8	4.9	.94	.86	3¾+
5.	9.0	9.2	6.9	5.9	1.02	.77	3½
6.	7.4	7.0	5.9	5.2	.95	.78	4
7.	7.1	6.5	5.4	4.0	.92	.76	3½+
8.	6.1	5.9	5.8	3.5	.97	.95	
9.	6.1	5.6	5.6	3.4	.92	.92	4
10.	6.0	5.0	5.0	3.1	.82	.83	
11.	5.7	5.5	5.0	3.1	.97	.88	3½
12.	5.0	4.9	4.5	2.7	.98	.90	3
13.	5.0	4.1	4.1	2.7	.82	.82	3¼
14.	4.9	5.6	4.1	3.1	1.14	.84	3¾
15.	4.6	4.4	4.0	2.5	.96	.87	3¼
16.	4.6	5.0	4.3	2.9	1.09	.94	3½
17.	4.3	4.0	4.0	3.1	.93	.93	
18.	3.5	3.2	3.9	1.8	.91	.83	
19.	3.4	3.1	2.6	1.9	.91	.76	2¾
20.	3.2	2.9	2.1	1.5	.91	.66	
21.	3.1	2.9	2.3	1.7	.94	.74	
22.	2.5	2.6	2.1	1.5	1.04	.84	3

TYPES: Holotype: Amer. Mus. Nat. Hist. 27112:1. Paratypes: Amer. Mus. Nat. Hist., Mus. Northern Ariz., Grand Canyon Nat. Park museum.

DISCUSSION: The ultimate diagnosis of species of *Naticopsis* appears to depend on color patterns. In the absence of preserved coloration, however, species must be established on the slight differences in shape shown by the fossils. For this reason, measurement of as many characters as possible on as many specimens as practical is offered.

This form bears closest resemblance to *N. deformis* Girty, but comparison with Girty's type specimens reveals that they are not the same. Girty's form is more transverse and more rotund than most of the Kaibab specimens, and has a lower spire. Superficial examination reveals other differences which, due to the rounded shape of both shells, cannot be measured.

Strong resemblance to a form identified by Girty (1909a, p. 463, pl. 10, figs. 3, 3a) as *Strophostylus subovatus* is evident, although identity of either Girty's specimen or the Kaibab forms with *S. subovatus* Worthen seems extremely doubtful. Girty in his later papers did not appear to recognize this similarity nor to discuss it under affinities of *N. deformis*.

This species also resembles *N. transversa* (Beede) in general shape. Although Knight (Newell, 1940) describes some specimens of *N. transversa* as having little or no transverse ornamentation, complete shoulder, as well as a less oblique outer lip, than is evident in *N. kaibabensis*, and are to be considered a different species. Because of the preservation as external molds, the aperture and parietal lip cannot

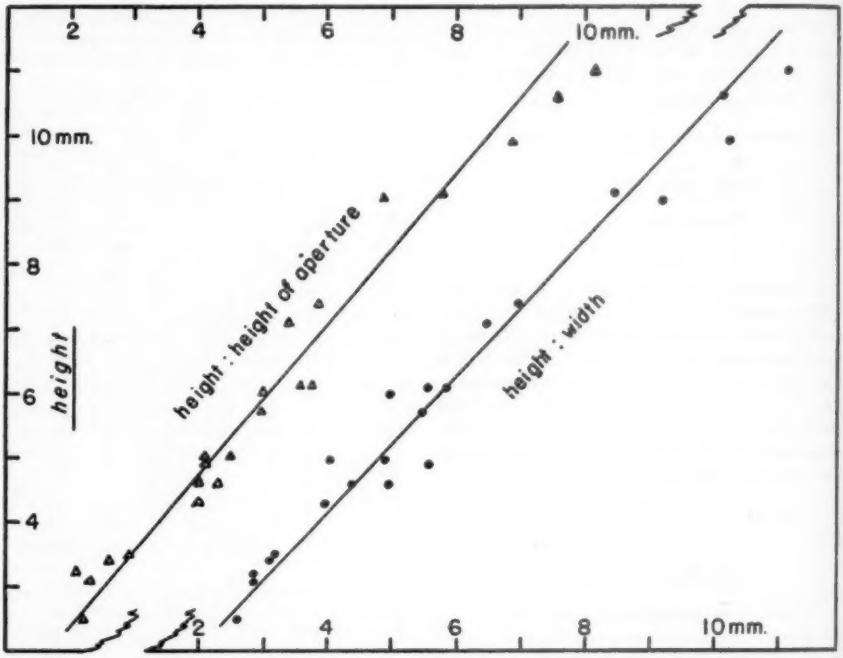

FIGURE 10.—RELATION OF WIDTH AND HEIGHT OF APERTURE TO HEIGHT IN *Naticopsis kaibabensis*

absence of any such ornamentation in the Kaibab specimens is considered sufficient evidence that they are separate species.

In shape, this form, especially certain of the juveniles, also resembles *N. nana* Meek and Worthen, but is more globose and has a less pronounced spire, while the shape of the aperture differs markedly. *N. remex* White has a more evenly rounded whorl, without any development of a shoulder. There is strong resemblance to the Mongolian form, *N. khurensis* Waagen, from which it differs in the more rounded base and the less oblique character of the aperture.

OCCURRENCE: Loc. 3 (abundant, silicified).

Naticopsis sp.

Pl. 5, fig. 12

A few specimens of *Naticopsis* from locality 1 show a larger size and a much more pronounced

be studied with the material at hand, so these specimens are not classified specifically. The discovery of more specimens may enable identification or show that these are a more mature form of *N. kaibabensis*.

OCCURRENCE: Loc. 1, bed 2 (common, external molds).

Superfamily CERITHIACEA

Family TURRITELLIDAE

Genus ***Orthonema*** Meek and Worthen 1861

Orthonema? striatonodosum sp. nov.

Pl. 5, figs. 13a–14

DESCRIPTION: Small, high-spired, many whorled gastropods of somewhat fusiform shape, the apical angle being always greater than the pleural angle; whorls numbering about 10; basal whorl nearly half entire height of shell. Suture shallow, appressed;

whorl profile very gently arching below suture; final whorl more strongly rounded at lower side of flank, forming an almost indiscernible angulation; base extended very slightly into an anterior canal. Aperture lozenge-shaped in cross-section; outer lip straight and almost vertical, extending below base to form a short anterior canal; inner lip thickened at canal, and with edge of rather thick parietal inductura forming an arc upward to suture.

Ornamentation consisting of a row of indistinct, low, vertically elongated nodes below line of suture, bounded above and below by poorly developed, striae-like furrows which are often obscured or erased by erosion; growth lines rarely evident, straight and almost vertically directed.

Nucleus seemingly smooth, with spiral furrows appearing before development of nodes.

MEASUREMENTS: The spires of most specimens are broken at the tip, and often the anterior canal is broken away, so measurements of height and number of whorls were estimated by comparison with a few more complete specimens. Dimensions in mm.:

	h	w	ha	bw	w/h	ϕ	aa	wh
1.	11.9	4.1	3.3	5.5	.34	8°	32°	8+
2.	11.3	3.8	3.3	4.9	.34	15	40	9
3.	11.0+	4.1		5.0	.37	18	32	8½
4.	10.8	4.2	3.7	4.4	.39	6	40	9+
5.	10.2	4.0	3.0+	4.5				
6.	10.1	3.9		5.0	.39	12	41	10½
7.	9.0	3.5			.39	14		9½
8.	9.0+	3.5			.39	13	35	9+
9.	9.0+	3.3			.37	9	47	7+
10.	8.9+	3.7	2.8	4.5+	.42	19	33	8+
11.	8.7	3.6						
12.	8.4	3.3	2.6	4.0	.39	9	43	7+

TYPES: Holotype: Amer. Mus. Nat. Hist. no. 27117:1. Paratypes: Am. Mus. Nat. Hist., Mus. Northern Ariz.

DISCUSSION: The specimens at hand show considerable variety in form. Although the majority tend to be quite high-spired and to have a very low pleural angle and an apical angle considerably greater, others give an impression of being rounded, with the apical angle close to 40°, while the pleural angle is very low, perhaps below 10°, so that considerable gibbosity is apparent.

There is much resemblance between this form and *Orthonema* sp. 1, described below. The latter, a single specimen, is two or three times as large and shows a definitely orthonematid bend in the upper part of the outer lip (as indicated in growth lines) and quite a strong angulation between the base and flanks. These characters may become pronounced only in advanced stages of ontogeny, so that *O.* sp. 1 is possibly a mature specimen of *O.? striatonodosum*.

The straight outer lip seen in specimens of *O.? striatonodosum* is not characteristic of the genus, though in its other characters this form resembles members of the genus. It is placed tentatively

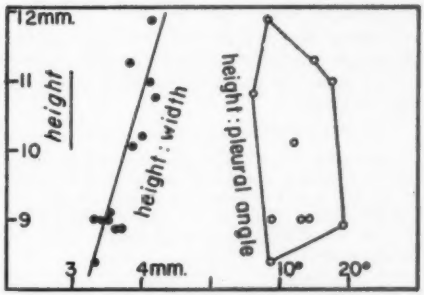

FIGURE 11.—RELATION OF WIDTH AND PLEURAL ANGLE TO HEIGHT IN *Orthonema? striatonodosum*

within the genus until further collections, possibly of specimens with well preserved apertures, can be made.

A form very like this occurs in the Word limestone no. 1 of the type locality, but has not yet been described.

Although in general shape this form strongly resembles *O. conicum* Meek and Worthen, from the Pennsylvanian of the Mississippi valley, it does not have the sinuosity of the outer lip or a distinct angulation at the base.

In ornamentation there is also some resemblance to *O. cerithioides* Mansuy. That Indochinese species differs from *O.? striatonodosum* in its more regularly conical shape, for it has little tendency toward fusiformity, and in its lack of striae above and below the row of nodes.

OCCURRENCE: Loc. 1, bed 9 (rare, external molds); loc. 3 (common, silicified).

Orthonema sp. 1

Pl. 5, fig. 18

DESCRIPTION: A high-spired, many whorled gastropod of medium size, having about 10 whorls and a pleural angle of 12½°; whorls regularly enlarging and overlapping so that basal whorl is about two-fifths the height of entire shell. Suture shallow, appressed, located just above a rounded but pronounced angulation dividing the base and sides of shell; shell profile sloping gently outward below suture for a short distance, forming a narrow,

steeply inclined shoulder, then turning abruptly vertical to form flanks, and rounding at basal angulation into an inclined, anomphalous base with a short anterior canal. Aperture oval, pointed above and leading below to anterior canal; outer lip directed gently and obliquely backward below suture to shoulder angle, where it becomes vertical and continues so, being radial on base.

Ornamentation includes some very obscure nodes along shoulder angle and a faint suggestion of spiral liration, especially on flanks; growth lines fine and often indistinct.

Nucleus unknown.

MEASUREMENTS: The single silicified specimen has the following dimensions. As the spire is broken at the tip, height is estimated. Height 25 mm. +; width 9.0 mm.; height of aperture 6.0 mm.; height of basal whorl 10.0 mm.; width/height ratio .36; pleural angle 12½°.

DISCUSSION: The specimen is similar in general shape and in its faint nodular ornamentation to the associated, more abundant small species *O.? striatonodosum*. Its growth lines, however, very distinctly bend forward above the shoulder angulation in true orthonematid fashion, and the basal angulation is considerably stronger than in the smaller forms. It is possible that these are characters which develop fully only in advanced stages of ontogeny, but the fact that they are evident in the smallest preserved whorls of the spire suggests that this is not merely a more mature *O.? striatonodosum*, but a different species, definitely one of the orthonematid group.

No other species of *Orthonema* is known to which this specimen can be assigned. It resembles in shape but not in ornamentation the Pennsylvanian species *O. salteri* (Meek and Worthen), and differs from *O. socorroense* Girty in the presence of a shoulder angulation and in the more rounded character of the basal angulation. It is twice as large as that form.

OCCURRENCE: Loc. 3 (very rare, silicified).

Orthonema? sp. 2

Pl. 5, fig. 15

A small, high-spired, trochiform gastropod of uncertain affinities shows strong superficial resemblance to *O. socorroense* Girty, from which it differs, however, in the faint sinuosity of the whorl profile. It also resembles *Taosia dozierensis* (Beede), but has none of the faint transverse undulations described by Knight (Newell, 1940, p. 310) in that genus, nor is there any sign of a median slit band. That it is a member of the genus *Orthonema* is not certain; growth lines revealing the shape of the outer lip can not be seen. It may possibly be a *Murchisonia* with the selenizone located extremely low on the whorl, as on some of the extreme variants of *M. gouldii* Beede described by Knight (Newell, 1940, p. 308).

OCCURRENCE: Loc. 1, bed 9 (rare, external molds).

Superfamily et family indet.

Genus et species indet. 2

Pl. 5, figs. 16, 17

A number of small, high-spired gastropods 4–12 mm. in height, having 8–10 gradually expanding volutions, are not well enough preserved to be assigned either generically or specifically. Growth lines and ornamentation are usually not distinguishable, though one specimen shows growth lines which indicate the outer lip is vertical below the suture, curving to backward obliquity about half way down the shell and forming a shallow sinus above the periphery, then directed forward across the periphery and base of the shell. One specimen shows a suggestion of vertical ribbing (which may however be an irregularity of preservation) and several others show spiral striation on the base and a single fine stria just above the periphery.

It is highly probable that more than one form is included here. Specimens bear a superficial resemblance to *Orthonema socorroense* Girty, but they may not be orthonematid in nature.

OCCURRENCE: Loc. 1, bed 9 (rare, external molds); loc. 3 (common, silicified).

PELECYPODA

Twenty-six pelecypods are here described, belonging to 22 genera. Two new genera and 8 new species are described. The pelecypods bear a resemblance to those of the Word limestone no. 1, but the similarity is not so pronounced as in the gastropods.

A chart of occurrence and relative abundance of pelecypods from the four faunules is presented below. Measurements of various forms are recorded in full. Where a large number of specimens made it practical, ratios of width to length and convexity to length have been presented graphically.

Abbreviations used in tables of measurements are as follows:

l	=	length
h	=	height
g	=	length of hinge
att	=	number of anterior teeth
ptt	=	number of posterior teeth
c	=	convexity, both valves together
½c	=	convexity of one valve
a	=	length of shell anterior to beak
b	=	height at beak, perpendicular to hinge

TABLE 2.—PELECYPODS, OCCURRENCE AND FREQUENCY CHART

	Loc. 1 bed 2	Loc. 1 bed 9	Loc. 2 bed 4	Loc. 3
Acanthopecten coloradoensis (Newberry)		x		
Allorisma terminale Hall	x	x		
Allorisma? juveniles				x
Alula gilberti (White)		x		
Astartella subquadrata Girty	xxx	xxx		xxx
Aviculopecten kaibabensis Newell	x	x	x	
Aviculopinna sagitta sp. nov.		x		
Bakevellia prora sp. nov.		xx	x	
Bakevellia cf. *B. sulcata* (Geinitz)				x
Dozierella sp. 1				x
Dozierella? sp. 2		x		
Edmondia sp.		x		
Goniophora cristata sp. nov.		x	x	x
Grammatodon politus (Girty)	xx	xx	x	x
Kaibabella curvilenata gen. et sp. nov.		xx	x	x
Manzanella cryptodentata sp. nov.		x		x
Myalinella? adunca sp. nov.		x		
Nuculana obesa White			xx	xx
Palaeonucula levatiformis (Walcott)	xxx	xxx	xxx	xxx
Pleurophorus albequus Beede	xxx	xx	xxx	x
Pleurophorus cf. *P. mexicanus* Girty		x		
Promytilus retusus sp. nov.	x	x	xx	
Rimmyjimina arcula gen. et sp. nov.				xx
Sanguinolites? sp.		xx	x	
Schizodus texanus Clifton		x		
Solemya parallela Beede and Rogers		x		x

x—rare
xx—common
xxx—abundant

Superfamily NUCULACEA

Family NUCULANIDAE

Genus *Nuculana* Linck 1807

Nuculana obesa White 1879

Pl. 6, figs. 1a-3

Nuculana obesa WHITE, U. S. Geol. and Geog. Survey Terr., Bull. 5 (1879), p. 216.

Nuculana obesa, WHITE, U. S. Geol. and Geog. Survey Terr. Wyo. and Idaho, Ann. Repts., vol. 12, pt. 1 (1883), p. 136, pl. 34, figs. 2a-c.

Leda obesa, GIRTY, U. S. Geol. Survey, Bull. 389 (1909), p. 76.

Leda obesa, GIRTY, U. S. Geol. Survey, Bull. 436 (1910), p. 40, pl. 4, figs. 7, 8.

Leda obesa, BRANSON, Missouri Univ. Studies, vol. 5, no. 2 (1930), p. 43, pl. 10, figs. 21, 22.

DESCRIPTION: Nuculoid pelecypods of moderate size, with posterior margin extended. Cardinal margin strongly arched anteriorly and continuous with anterior margin, which arches below smoothly into gently arcuate ventral margin; cardinal margin concave posteriorly and continuous with much extended, upward-curving posterior margin, which gapes at its truncated termination. Beaks small, posteriorly directed; posterior umbonal ridge sharp, concave upward.

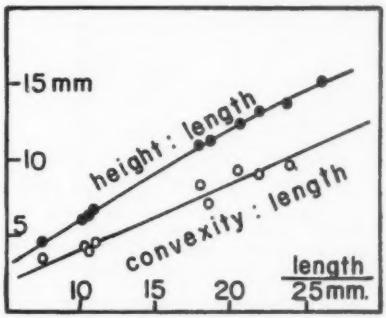

FIGURE 12.—RELATION OF HEIGHT AND CONVEXITY TO LENGTH IN *Nuculana obesa*

Ornamentation fine and somewhat irregular concentric lirae, spaced 3–5 per mm., becoming more crowded toward umbo; lirae broad and flat, separated by narrow furrows, and independent of growth lines except near margin of adults; growth lines obscure.

Escutcheon elongate and pointed; dentition taxodont, with about 10–16 closely spaced, vertically elongated, sharp teeth anterior to beak and usually 9–14 posterior to beak; distally the posterior teeth become distinctly chevron-shaped; pallial line sinuate and commonly deep in adult shells; anterior muscle scar circular, only slightly depressed, generally indistinct; a rounded internal ridge bearing irregular scars of pedal muscles near umbo and bordered by depressions, extending vertically downward from umbonal region to about middle of shell. Posterior adductor impression not observed.

Constrictions in shell during growth are occasional, most shells over 10 mm. long showing at

least a slight constriction near ventral margin, at a position corresponding externally to pallial line. At this constriction, the lirae are truncated by succeeding lirae. There is a slight change in length during growth, youthful stages being relatively shorter than adult. Posterior siphonal part of shell appears proportionately more slender in adults than in juveniles.

MEASUREMENTS: Ten silicified specimens have the following dimensions (in mm.):

	l	h	c	h/l	c/l
1.	26+	15.2		.58	
2.	24.0	13.7	9.6	.57	.40
3.	22+	13.3	9.1	.60	.41
4.	20.5+	12.6	9.4	.61	.46
5.	18.7	11.4	7.1	.61	.38
6.	18.0	11.0	8.4	.61	.47
7.	10.9	6.8	4.6	.62	.42
8.	10.6	6.6	4.0	.62	.38
9.	10.2	6.2	4.4	.61	.43
10.	7.5	4.8	3.6	.64	.48

Three internal molds are intermediate in size, though measurements are not directly comparable with those above because the thickness of the shell is lacking.

11.	18+	8.2	
12.	15+	8.7	
13.	12.5+	6.6	

Figure 12 shows the slight change in height-length ratio during growth. There is seemingly no change in convexity.

DISCUSSION: In shape, size, and ornamentation, this form agrees closely with White's original definition of *Nuculana obesa*, from specimens collected from the Kaibab formation north of Grand Canyon.

Increase in the ratio of height to length during successive growth stages, as described by Girty (1910), is evident but not pronounced in these specimens. A change in convexity, also noted by Girty, is not so evident, as the convexity varies considerably at all growth stages.

OCCURRENCE: Loc. 2, bed 4 (common, external and internal molds); loc. 3 (common, silicified).

Genus *Palaeonucula* Quenstedt 1930

Palaeonucula levatiformis (Walcott) 1884

Pl. 6, figs. 4–9

Nucula levatiforme WALCOTT, U. S. Geol. Survey, Mon. 8 (1884), p. 241, pl. 22, figs. 1, 1a.
Nucula levatiformis, GIRTY, U. S. Geol. Survey, Bull. 389 (1909), p. 74, pl. 10, figs. 7, 8.
Nucula levatiformis, CLIFTON, Jour. Paleont., vol. 16 (1942), p. 693.

DESCRIPTION: Very small, subtriangular nuculid, a little longer than high, with biconvexity of the 2 valves somewhat more than half the length. Anterior margin irregularly convex, forming a rounded bulge below beak; posterior margin almost perpendicular to anterior, gently and regularly convex; ventral margin quite convex and rounding abruptly into anterior margin, less abruptly into posterior margin. Beak pointed, prosogyre, not strongly incurved; shell evenly convex, without umbonal ridge.

Ornamentation of fine, low, evenly spaced concentric lirae, spaced about 10 per mm.; one or more concentric growth constrictions near ventral margin of some shells.

Dentition taxodont, with about 10–13 anterior teeth and 6–9 posterior teeth in large individuals; teeth increasing in size and spacing away from beak, the outermost few often being considerably enlarged; a triangular resilium lies under beak. Pallial line and anterior muscle scar usually not visible; posterior scar strongly impressed along its anterodorsal margin.

Although proportion of height to length of the shell shows no regular change with growth, relative convexity tends to increase during ontogeny. Occasional strong growth constrictions are seen in a number of large shells, often more than one in a single shell.

MEASUREMENTS: Sixty specimens were selected for measurement. Dimensions in mm.:

	l	h	c	c/l	h/l		l	h	c	c/l	h/l
1.	7.3	6.0	4.5	.61	.82	31.	5.6	4.7	3.6	.64	.84
2.	7.1	6.4	4.6	.64	.90	32.	5.6	4.7	3.4	.61	.84
3.	7.1	5.9	4.2	.59	.83	33.	5.6	4.6	3.4	.61	.82
4.	7.0	5.9	5.3	.76	.84	34.	5.6	5.0	3.6	.64	.89
5.	6.8	5.7	4.3	.63	.84	35.	5.5	4.7	3.0	.67	.86
6.	6.7	5.7	4.6	.69	.85	36.	5.4	4.6	2.9	.54	.85
7.	6.7	5.6	4.0	.60	.84	37.	5.4	4.6	3.4	.63	.85
8.	6.6	5.5	4.2	.64	.83	38.	5.4	4.6	3.4	.63	.86
9.	6.6	5.5	4.6	.70	.83	39.	5.3	4.7	3.6	.68	.89
10.	6.6	5.3	4.6	.70	.80	40.	5.3	4.6	3.8	.72	.87
11.	6.6	5.4	4.8	.73	.82	41.	5.1	4.5	3.2	.63	.88
12.	6.5	5.4	3.8	.58	.83	42.	5.0	4.0	3.0	.60	.80
13.	6.5	5.5	4.2	.65	.85	43.	4.7	4.0	3.0	.64	.85
14.	6.5	5.2	3.7	.57	.80	44.	4.6	4.0	2.6	.57	.87
15.	6.5	5.4	4.4	.68	.83	45.	4.6	3.9	2.7	.59	.85
16.	6.4	5.4	3.6	.56	.85	46.	4.5	3.7	2.8	.62	.82
17.	6.4	5.5	4.5	.70	.86	47.	4.4	3.6	2.5	.56	.82
18.	6.3	5.2	4.4	.70	.83	48.	4.4	3.7	2.5	.57	.84
19.	6.3	5.3	4.0	.64	.84	49.	4.3	3.4	2.4	.56	.79
20.	6.3	5.4	4.7	.75	.86	50.	4.3	3.6	2.5	.58	.84
21.	6.0	5.2	3.7	.62	.87	51.	4.1	3.5	2.5	.58	.84
22.	6.0	5.1	4.2	.70	.85	52.	3.9	3.3	2.8	.72	.85
23.	6.0	5.4	4.4	.73	.90	53.	3.7	3.4	2.3	.62	.92
24.	5.9	5.2	4.1	.70	.88	54.	3.6	3.0	2.0	.66	.83
25.	5.8	5.0	3.8	.66	.86	55.	3.6	3.1	2.2	.61	.86
26.	5.7	4.8	3.6	.63	.84	56.	3.3	2.6	1.8	.54	.84
27.	5.7	5.0	4.0	.70	.88	57.	3.3	2.6	2.0	.61	.79
28.	5.7	4.8	3.4	.60	.84	58.	2.7	2.1	1.5	.56	.78
29.	5.7	4.6	3.4	.60	.81	59.	2.2	1.7	1.3	.59	.77
30.	5.7	5.0	3.8	.67	.88	60.	2.0	1.6	1.3	.65	.80

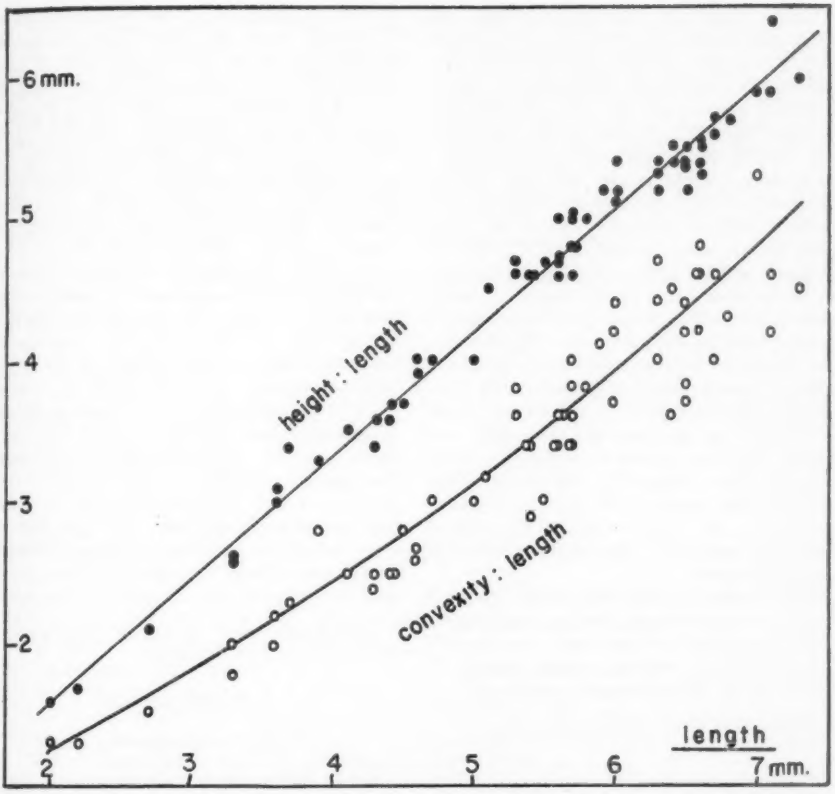

FIGURE 13.—RELATION OF HEIGHT AND CONVEXITY TO LENGTH IN *Palaeonucula levatiformis*

DISCUSSION: The similarity of size, shape, and surface sculpture of Kaibab material to those of Walcott's specimens of *P. levatiformis* is pronounced, and agreement with forms identified as "*Nucula levatiformis*" by Girty confirm the assignment to that species. There is some similarity to *P. montpelierensis* Girty, a form much the same in proportions of length and height, but slightly less convex than *P. levatiformis*, and bearing finer concentric striae. It seems likely, as Girty suggests, that the 2 forms are members of a single long-ranging and locally abundant species.

OCCURRENCE: Loc. 1, beds 1, 9 (abundant, external and internal molds); loc. 2, bed 4 (abundant, external and internal molds); loc. 3 (abundant, silicified).

Superfamily?

Family MANZANELLIDAE

Genus *Manzanella* Girty 1909

The taxonomic position of the genus *Manzanella* is very uncertain. It differs from other pelecypods in the possession of an enlarged anterior lamellar cardinal tooth, associated with reduced posterior cardinal teeth. There is some resemblance to the family Nuculinidae, but in that family as in the genus *Nuculina*, the large lamellar tooth appears to be posterior, and the taxodont teeth anterior.

Manzanella cryptodentata sp. nov.

Pl. 6, figs. 11a–14

DESCRIPTION: Small, thick-shelled, transversely ovate, strongly convex pelecypods having height equal to 0.8–0.9 the length, and biconvexity equal to about 0.6–0.7 the length. Margins rounded and without angulations, usually slightly truncate posteriorly, but in general oval in plan, somewhat expanded anteriorly; cardinal margin slightly flattened anterior to beak; beak thick, short, prosogyre, located slightly posterior to middle; umbonal or siphonal ridge lacking.

Ornamentation lacking; growth lines fine, irregular, with occasional weak growth constrictions.

Lunule very small, subtriangular, lying just under beak; escutcheon well defined, with a narrow, arcuate ligament groove; dentition actinodont, with one or more strong but short, oblique, rounded, posteriorly directed cardinal teeth in left valve and corresponding sockets in right valve; a low, vertically directed cardinal tooth in right valve with a triangular socket just in front of cardinal tooth of left valve; a strong, very prominent lamellar anterior cardinal tooth in each valve, that of left valve fitting into a socket between anterior tooth and thickened cardinal margin of right valve, and bearing on its lower side a lamellar socket to receive tooth of right valve; anterior tooth buttressed by a strong, rounded, thick ridge extending down into shell. Ligament external, opisthodetic, lying in a narrow arcuate groove above posterior teeth. Anterior and posterior adductor muscles almost equal, anterior perhaps the larger and more deeply impressed, lying just anterior to thickened buttress; a depressed area bounds the buttress posteriorly and ventrally; anterior and posterior accessory muscle pits well marked, lying at extremities of hinge plate, just above adductor scars; pallial line apparently simple.

Little change in proportion during growth is evident although young specimens are slightly thinner proportionately than older ones; the small oblique posterior teeth apparently increase in length, but not in number, with growth.

MEASUREMENTS: (in mm.)

	l	h	c	h/l	c/l
1.	11.4	9.5	7.0	.83	.62
2.	11.0	9.8	7.6	.89	.69
3.	10.2	9.0	6.6	.88	.65
4.	10.0	8.5	6.6	.83	.64
5.	9.7+	8.0	5.8	.84	.60
6.	9.6	8.0	6.0	.83	.63
7.	9.1	8.0	6.4	.88	.70
8.	8.5	6.4	4.6	.75	.54
9.	8.2	6.5+	5.2	.79	.63
10.	5.7+	4.3	3.0	.75	.53
11.	5.6	4.5	3.2	.80	.57
12.	5.4	4.2	2.6	.78	.48

Girty's specimens of *M. elliptica:*

	l	h	c	h/l	c/l
1.	12.1	10.0+	9.8	.83	.81
2.	10.1	9.1	7.1	.91	.73

TYPES: Holotype: Amer. Mus. Nat. Hist. 27101:1. Paratypes: Amer. Mus. Nat. Hist., and Mus. Northern Ariz.

DISCUSSION: The posterior elements of the dentition of these specimens differs from Girty's *Manzanella elliptica* from the Yeso (Leonardian), although other characters of the shells are almost identical. Examination of the type specimens of *M. elliptica* shows that Girty's figure is accurate. In spite of difference in dentition, there is close similarity in other characters of the two forms. Of the Kaibab specimens, only one small left valve shows the posterior teeth well. In it there are 3 almost straight, oblique, posterior cardinals. On larger specimens the teeth appear to become longer, and lamellar, and to lie almost parallel to each other, below the escutcheon. The teeth are clearly not taxodont, as Girty described them.

The reason for differences in dentition between two shells otherwise so similar is not apparent. For lack of intermediate or transitional forms, the Kaibab specimens are here treated as a new species, but such differences may be induced, in part at least, by variations in ecologic conditions. Further study of the influence of environment on the development of dentition is necessary, and may lead to the conclusion that the two forms of *Manzanella* are conspecific. In such a case, the thicker shell substance of Girty's larger specimen and the higher beak and more strongly arched valves of both his types may also be interpreted as ecologic differences or may be attributed to geographic differentiation, since the two forms are of about the same age.

OCCURRENCE: Loc. 1, bed 9 (rare, external molds); loc. 3 (rare, silicified).

Superfamily ARCACEA

Family GRAMMATODONTIDAE

Genus *Grammatodon* Meek and Hayden 1860

Grammatodon politus (Girty) 1909

Pl. 7, figs. 1a–2b

Parallelodon politus GIRTY, U. S. Geol. Survey, Prof. Paper 58 (1909), p. 424, pl. 9, fig. 25.

DESCRIPTION: Transverse shells of medium size, with height usually a little over half the length, and convexity about 0.4 the length. Cardinal margin almost straight; anterior margin obliquely rounded, forming an acute angle with cardinal margin, and rounding gradually into ventral margin; ventral margin almost straight, though sometimes with a slight sinus about two-fifths the distance toward posterior margin, diverging from hingeline toward posterior; posterior margin rounded below, obliquely truncated above, forming an angle of about 120° to 140° with cardinal margin; beak low, anteriorly directed; umbo flattened, or, sometimes, with a shallow sulcus obscure except in very young individuals.

Radial ornamentation lacking; growth lines irregular and locally lamellose.

Dentition consisting of 2–5 oblique anterior teeth, the anterior 2 or 3 in large specimens being the most prominent, with corresponding sockets in each valve, and of 2 or 3 diverging lamellar teeth with corresponding sockets; number of teeth increasing with growth; ligament external, amphidetic; pallial line simple; muscle scars not well shown.

There appears to be no appreciable change in proportions during growth.

directed backward from cardinal margin at an angle of 120°, and rounding below into ventral margin, which is almost straight; anterior margin sharply rounded. Beak not well preserved, probably low and lying near anterior end; convexity of shell apparently greatest at point two-thirds the distance below cardinal margin.

Ornamentation lacking; growth lines irregular except near ventral margin, where they are very closely spaced.

MEASUREMENTS: Four silicified specimens and seven internal molds have the following dimensions (in mm.):

	l	h	c	h/l	c/l	g	a	b
1.	25.7	12.7	9.4	.49	.37	21.0	5.2+	10.3 (mold)
2.	20.0	11.0		.55		15.8	3.9	10.0 (mold)
3.	17.7	9.0	8+	.51	.45	14.1	3.3	8.0 (mold)
4.	15.2	7.8	6.4	.51	.42	11.0	3.0	6.9
5.	13.3	7.0		.53		10.8		(mold)
6.	12.3	5.8	6.0	.47	.49	9.9	2.0	5.8 (mold)
7.	10.5	6.0		.57				(mold)
8.	7.8	4.3		.55				
9.	6.8	4.0	2.8	.59	.41	5.3	1.5	3.3 (mold)
10.	6.7+	3.3+	2.8	.50+	.42	5.3	1.1	3.1
11.	4.8	2.9	2.0	.60	.42		1.0	2.7

DISCUSSION: This form strongly resembles *G. politus* (Girty) in its lack of radial ornamentation. Some specimens reveal a gentle sinuosity of the ventral border not reported by Girty, but his specimens were exceedingly fragmentary and not very abundant.

There is close affinity also with the Pennsylvanian form *G. obsoletus* Meek, which has a distinct ventral sinus but is somewhat more elongate than this form and bears obscure radial ornamentation near the hingeline behind the umbo.

Most other forms of this genus bear distinct radial ornamentation and so differ markedly from the present form.

OCCURRENCE: Loc. 1, beds 2, 9 (common, external and internal molds); loc. 2, bed 4 (rare, juvenile internal and external molds); loc. 3 (rare, silicified).

Superfamily PTERIACEA

Family PINNIDAE

Genus *Aviculopinna* Meek 1867

Aviculopinna sagitta sp. nov.

Pl. 6, fig. 10

DESCRIPTION: Highly oblique, elongate pelecypods with straight hinge and subterminal beak, and with cardinal and ventral margins diverging at about 9°. Cardinal margin straight, somewhat thickened into a narrow, thread-like ridge which becomes stronger posteriorly; posterior margin

Internal structures unknown.

MEASUREMENTS: The holotype has the following dimensions: length 100 mm.; height 20 mm.; thickness 8 mm. +.

TYPES: Holotype: Mus. Northern Ariz. G2.1300.

DISCUSSION: The external mold showing the above characters is unlike any previously described Pennsylvanian or Permian species of *Aviculopinna*. It is much more acute than *A. nebraskensis* Beede and not so large. It differs from *A. peracuta* (Shumard) in its obtuse posterior angulation, and from *A. illinoisensis* Worthen in its straight cardinal margin. *A. americana* Meek is not as thick and shows besides a sinuosity in the posterior margin and a few radiating ridges. *A. pinnaeformis* (Geinitz) is apparently much smaller and also shows radiating striae. *A. knightii* Beede, a much larger species, has the cardinal and ventral margins almost parallel.

Although the material is not complete and but a single specimen is available, that specimen is so obviously distinct from previously described forms that it warrants being named the holotype of a new species.

OCCURRENCE: Loc. 1, bed 9 (one external mold). Fragmentary external molds were observed in various parts of the Kaibab section, and often reached a much greater size than the present specimen. They may not, however, be conspecific.

Family LEIOPTERIIDAE

Genus *Dozierella* Newell 1940

Dozierella sp. 1

Pl. 7, figs. 4a–5

A single, somewhat fragmentary left valve, and a tiny juvenile right valve of a small pterioid are distinguished from specimens of *Bakevellia prora* sp. nov. by their ornamentation and dentition. The left valve is marked by fine, wavy, but rather regularly spaced concentric lirae, following the growth lines, and by fairly widely spaced, stronger growth constrictions. The posterior sinus is only feebly developed, and no anterior sinus is discernible in the broken shell. The left valve bears a single long, posterior tooth almost parallel to the cardinal margin. Anterior dentition is not visible.

The right valve bears 3 small cardinal teeth, the anterior one almost parallel to the anterior margin, the second parallel to the cardinal margin, and the third oblique to the cardinal margin, an arrangement similar to that described for *Dozierella*. At least one posterior tooth is present, diverging gently from the cardinal margin. The arcoid ligamental area typical of *Dozierella* is not observable in these specimens.

MEASUREMENTS: (in mm.)

	l	h	c	g	gp	valve
1.	7.5	4.7			5.0	left
2.	3.4	2.1	0.7	2.6	2.2	right

gp = hinge posterior to beak.

OCCURRENCE: Loc. 3 (very rare, silicified).

Dozierella? sp. 2

Pl. 7, fig. 3

The internal mold of a right valve of a small pterioid is very oblique in shape, has a posterior auricle, and several subparallel posterior lamellar teeth. The single specimen is inadequate, however, for substantial description or comparison. It may belong to *Dozierella*, though the dentition does not appear closely similar to that of the genotype.

MEASUREMENTS: Length 9.3 mm.; height 4.7 mm.; convexity 1.0 mm.; length of hinge 5.2 mm.; maximum diameter 10.0 mm.

OCCURRENCE: Loc. 1, bed 9 (one internal mold).

Family ISOGNOMONTIDAE

Genus *Bakevellia* King 1848

Bakevellia prora sp. nov.

Pl. 7, fig. 10

DESCRIPTION: Small, strongly oblique isognomontids, probably inequivalved and with right valve thinner, more delicate, and less often preserved than left. Hingeline long and straight, about 0.9 the length of shell; anterior margin protruding, rounded, merging at a gentle sinus into gently convex ventral margin; posterior margin strongly concave below hinge, forming a concave emargination in posterior auricle, then turning with sharp convexity to meet ventral margin. Valve strongly convex transversely except for flattened posterior auricle and a shallow sulcus extending from anterior side of umbo almost vertically to ventral margin, delimiting anterior auricle; anterior sulcus bounded posteriorly by a sharp though slight change in convexity of shell. Growth lines irregular over most of shell, often lamellose anteriorly and near ventral margin, fairly regular only on posterior auricle.

Hinge of left valve with a long posterior groove bounded above and below by narrow ridges and bearing 3 or more irregularly spaced, oval multivincular ligament pits, one just below beak and two about a third the distance behind it; anteriorly a fairly strong lamellar tooth, with a small linear socket above it, extends forward $\frac{2}{3}$ the distance to anterior margin. Dentition of right valve not well known, apparently consisting of an anterior oblique tooth and a posterior groove similar to that of left valve.

MEASUREMENTS: Eleven molds of left valves were collected, and only one of a right valve. Dimensions in mm.:

	h	l	$\frac{1}{2}$c	hl
1.	7.0	10.5	2.1	
2.	6.1			
3.	5.9	9.0	2.2	8.0
4.	5.6	8.9	1.6	7.3
5.	5.5	9.0	1.8	8.3
6.	5.4	10.4	1.9	9.5 (holotype)
7.	5.4	8.2	1.7	7.3
8.	5.3	10+	2+	8+
9.	4.7	7.6	2.1	6.5
10.	4.4	6.5	2.0+	5.2+
11.	4.2	7.3+	1.8+	6.9+
12.	4.7	8.3	1.2	6.5 (rt. valve)

TYPES: Holotype: Mus. Northern Ariz. G2.1307. Paratypes: Mus. Northern Ariz.

DISCUSSION: These specimens differ from previously described members of *Bakevellia* in shape and convexity, and in length of posterior auricle. They are further distinguished by a sharp change in convexity of the shell along the anterior sulcus.

B. prora resembles *Pteria? guadalupensis* Girty but the posterior sinus is not so deep nor is the shell as long and slender as in Girty's species.

OCCURRENCE: Loc. 1, bed 9 (common, external and internal molds); loc. 2, bed 4 (rare, external and internal molds).

Bakevellia* cf. *B. sulcata (Geinitz) 1877

Pl. 7, figs. 6-9

DESCRIPTION: Very small, strongly oblique isognomontids, slightly inequivalved, with right valve somewhat less convex than left. Hingeline straight, extended posteriorly along auricle; posterior margins seemingly strongly extended, but posterior auricle partly broken away in all specimens at hand; anterior margin protruding, rounded, the anterior auricle being defined by a broad sulcus directed almost perpendicular to hinge; ventral margin gently convex except for shallow anterior sinus, and rounding into posterior margin rather sharply.

Left valve ornamented by a prominent ridge on each side of anterior sulcus, increasing in prominence and diverging toward ventral margin; right valve unornamented; growth lines fine, commonly indistinct.

Oblique ligament pits are present along ligamental area posterior to beaks; anterior to beak in left valve there is a large oblique tooth; other characters of hinge not observed.

MEASUREMENTS: In all specimens the posterior auricle is broken, so total length can only be estimated. Specimens 1–3 are doubtless quite immature; specimen 4, though much larger, is very incomplete. Dimensions in mm.:

	l	h	c	valve
1.	5.0+	2.6+		right
2.	4.5+	2.7		right
3.	5.2	3.3	2.0	both
4.		5.4		left

DISCUSSION: This form resembles a group of species, placed by different authors in several genera, characterized by two or more ridges defining an anterior sulcus. To this group belong *Bakevellia sulcata* (Geinitz) and *Pteria richardsoni* Girty, both somewhat similar in shape to the present form.

OCCURRENCE: Loc. 3 (rare, silicified).

Superfamily TRIGONIACEA

Family TRIGONIIDAE

Genus ***Schizodus*** King 1844

Schizodus texanus Clifton 1942

Pl. 7, figs. 11a, b

Schizodus wheeleri, WHITE, U. S. Geog. Survey, W. 100th Merid. Rept., vol. 4 (1877), p. 154, pl. 11, figs. 6a, b.

Schizodus wheeleri, GIRTY, U. S. Geol. Survey, Bull. 389 (1909), p. 82, pl. 10, fig. 6.

Schizodus texanus CLIFTON, Jour. Paleont., vol. 16 (1942), p. 691, pl. 101, figs. 20–28; pl. 102, figs. 10–13.

DESCRIPTION: Trigonal shells of medium size and moderate convexity, having a short, arcuate cardinal margin, a circular anterior margin curving continuously into arcuate ventral margin, and an obliquely truncated, slightly convex posterior margin. Umbones high, with beaks pointed, strongly incurved, slightly opisthogyre; umbonal ridge prominent on exterior of shell, slightly less so on internal molds, dividing shell into an anterior, more or less strongly convex region and a posterior, flattened region.

Ornamentation of fine, regularly spaced (about 7 in 5 mm.), concentric lirae, separated by flat interspaces; lirae rarely impressed on internal molds.

Dentition not readily described from interior molds, but similar to that described by Clifton for this species. Anterior muscle scar of moderate size, bounded by a slight ridge posteriorly; posterior muscle scar of similar size, with a slight ridge around its dorsal and anterior margins. Pallial line simple.

MEASUREMENTS: (in mm.)

	l	h	½c	valve
1.	31	23	6	right
2.	30	23	7	left
3.	27	27	7	left
4.	27	22	8	right
5.	26	21	6	right
6.	25	20	6	right
7.	25	20	6	right
8.	25	20	5.5	right
9.	23	18	5	left
10.	23	19	6	left
11.	22.5	17	4.5	right
12.	19	16.5	5	right
13.	16	13	4	right
14.	6.9		2.0	right
15.	6.5	5.2	1.5	right

DISCUSSION: This species was proposed by Clifton to include specimens identified by White and Girty as *S. wheeleri* Swallow, a Pennsylvanian species. Clifton reports it from the Blaine and Dog Creek formations, as well as from the San Andres of New Mexico. Kaibab individuals correspond well with Clifton's examples and with those of White and Girty.

OCCURRENCE: Loc. 1, bed 9 (rare, external and internal molds); molds are also very abundant in debris from excavations at loc. 1, and are believed to have come from horizons lower than the section measured.

Superfamily PECTINACEA

Family AVICULOPECTINIDAE

Genus *Aviculopecten* McCoy 1851

Aviculopecten kaibabensis Newell 1937

Pl. 8, figs. 1–7

Aviculopecten kaibabensis NEWELL, Kansas State Geol. Survey, vol. 10 (1937), p. 60, pl. 4, figs. 17, 18.

DESCRIPTION: Large, circular pectinoids with strongly convex left valve and somewhat flatter right valve. Hingeline straight, seemingly not as long as body of shell; anterior auricle of left valve not strongly extended, separated from remainder of valve by an abrupt vertical flexure; byssal sinus shallow; posterior auricle of left valve not strongly differentiated; umbonal ridge lacking. Right valve probably smaller than left, gently convex and with a deeply impressed byssal notch and extended anterior auricle; posterior auricle pointed, gently concave below hinge, divided from body of shell by a low ridge.

Ornamentation of left valve consisting of many closely spaced costae; about 10 primary costae remaining slightly more prominent than secondary and later costae throughout height of valve; later costae added by intercalation so that entire valve appears about evenly costate; on interior of left valve, the impression of external ornamentation can be observed, but primary and later costae cannot be differentiated, and all costae appear sharply and finely striated longitudinally; anterior auricle of left valve with about 4 primary costae and 2–4 costae intercalated between each primary pair; posterior auricle with 12–15 widely spaced costae; growth lines fine, evenly spaced, distinct only at margins and on auricles. Right valve shown only by internal molds, apparently smooth or with subdued radial ornamentation; anterior auricle of right valve probably with radial ornamentation.

MEASUREMENTS: A number of almost complete shells are available; measurements of others are in part estimated. Dimensions in mm.:

	l	h	⅛c	valve
1.	65+	60+	17	left
1.	65+	60+	9	right
2.	73+	75+	12	left
3.	49+			left
4.	43+	45	11	left
5.	27	31	8	left
6.	22	18	3.5	left
7.	12.1	13.7	3.2	left
8.	11	11	2.5	left
9.	10+	11		left
10.	9.5	10	2	left
11.	9	9.5	1.2	left
12.	8.0	7.2	1.4	left
13.	49	36	5	right
14.	40+	35	3	right
15.	26+	22	2	right
16.	25+	20+	2	right
17.	9	8	0.2	right
18.	6.3	6.5	0.4	right

DISCUSSION: This species was first described from three specimens collected from the Kaibab formation at Padre Canyon, about 12 miles east of locality 1. Left valves in the present collection show a wide range in size and hence illustrate the species much better than the original material. One complete internal mold shows that the right valve was somewhat flatter than the left, and lacked the strong ornamentation of that valve. Numerous internal molds of right valves found in association with the left valves of the species also show less convexity and a smoother surface than do the left valves, and although none of them are as large as some of the left valves in the collection they are believed to represent the same species.

OCCURRENCE: Loc. 1, bed 2 (rare, external and internal molds); bed 9 (rare, external and internal molds); loc. 2, bed 4 (rare, external and internal molds of juveniles). Abundant specimens occur in debris from excavations at loc. 1, and seem to represent horizons lower than the measured section.

Genus *Acanthopecten* Girty 1903

Acanthopecten coloradoensis (Newberry) 1861

Pl. 8, fig. 8

Pecten (Monotis?) coloradoensis NEWBERRY, Ives Colo. Explor. Exped. (1861), p. 121, pl. 1, figs. 6, 6a.

Acanthopecten coloradoensis, STOYANOW, Geol. Soc. Am., Bull., vol. 47 (1936), p. 532.

Acanthopecten coloradoensis, NEWELL, Kans. State Geol. Survey, Bull., vol. 10 (1937), p. 75, pl. 12, figs. 7a, b, 13–15b.

A small fragment having the characteristic ornamentation of this species is in the present collection. It is, however, inadequate for description.

OCCURRENCE: Loc. 1, bed 9 (very rare, external mold).

Superfamily MYTILACEA

Family MYTILIDAE

Genus *Promytilus* Newell 1942

Promytilus retusus sp. nov.

Pl. 7, figs. 12–15

DESCRIPTION: Elongate, oblique, inflated mytilids with terminal beaks. Cardinal line very gently

arcuate, about half to three-fourths the length of shell; posterior margin curved, meeting cardinal margin at an angle of 130° or more, and rounding regularly into ventral margin; ventral margin oblique, slightly concave, continuing with slightly increasing convexity near anterior margin, which is very slightly expanded into an anterior lobe. Beak bluntly pointed; umbonal ridge prominent, forming an angle of about 45°–50° with cardinal margin near beak, up to 60° near ventral margin in larger shells.

Shell without ornamentation.

Hinge not well preserved in specimens at hand, but apparently edentulous, with a linear nymph for support of ligament; ligament groove wide and concave. Muscle scars and pallial line not visible.

MEASUREMENTS: Specimens are internal molds, hence measurements necessarily represent slightly less than external shell dimensions. Dimensions in mm.:

	l	h	½c	md	valve
1.	26.5	22.1	4.2	29.9	right
2.	17.4	14.0	3.9	19.8	left (holotype)
3.	17.4±	12.5	3.6	18.1±	left
4.	15.0	12.7	3.2	18.5	right
5.	13.0	10.0	3.7	15.2	left
6.	12.6±	12.0	2.4	15.4	right
7.	12.3	10.6	3.5	14.7	right
8.	11.3	8.8	2.0	11.9	left
9.	10.3	7.4	1.9	10.4	right
10.	9.7	5.5	1.8	10.5	left
11.	8.7	6.9	1.6	9.7	left
12.	8.6	7.0	1.8	9.0	right
13.	8.0	7.0	1.9	8.8	left
14.	6.8	5.8	1.5	8.8	left
15.	6.6	5.8	1.5	8.8	left

md = maximum dimension, measured obliquely from beak posteroventrally.

TYPES: Holotype: Mus. Northern Ariz. G2.347. Paratypes: Mus. Northern Ariz.

DISCUSSION: The only species of *Promytilus* resembling this in size is a form identified by White (1877) as "*Myalina swallovi* McChesney," from the Fort Apache limestone, Camp Apache, Arizona. White's illustration shows his form to be more strongly curved and to have the anterior lobe more fully developed so that the beaks are not quite terminal. The two forms, though slightly dissimilar in age, may be members of the same species. Since White's form obviously is not *Promytilus swallovi*, the present form is described as new.

The Kaibab species is deceptively similar to small specimens of *Myalina wyomingensis*, but appears to be equivalved, and therefore not a *Myalina*.

OCCURRENCE: Loc. 1, bed 2 (very rare, internal and external molds), bed 9 (rare, internal molds); loc. 2, bed 4 (common, internal and external molds).

Superfamily MYTILACEA?

Family MODIOLOPSIDAE?

Genus *Goniophora* Phillips 1848

Goniophora cristata sp. nov.

Pl. 8, figs. 9a–11b

DESCRIPTION: Small, elongate, angular pelecypods having an exceedingly high and prominent umbonal ridge. Cardinal margin almost straight, about half maximum length of shell; posterior margin oblique and arcuate, making an angle of about 50° with cardinal margin; anterior margin strongly concave for a short distance just below beak, then bulging forward strongly so that maximum forward projection lies about half way between cardinal and ventral margins; ventral margin sinuate, rounding with regular convexity into anterior margin, forming a very acute angle with posterior margin; beak incurved and anteriorly directed; shell strongly convex in front, flattened over most of its surface to the high, acute, flange-like umbonal ridge, behind which is a flattened area almost perpendicular to plane of shell; umbonal flange extending to ventral margin. Lunule deep, semicircular on each valve, its widest point anterior to its center; escutcheon long and very narrow, depressed only slightly below posterior area.

Ornamentation, other than umbonal crest, about 6 or 7 concentric lamellose ridges on and near umbo, following growth lines; remainder of shell without concentric lamellae, but with faint growth lines and even fainter and usually obscured radial liration.

Hinge and dentition dysodont; a triangular cardinal tooth in left valve, surrounded above and in front by an arc-shaped socket; right valve with a thin, sharp-edged, arcuate projection, having a shallow depression on lower surface which serves as a socket for cardinal tooth of left valve, but which does not completely embrace that tooth; a strong, rounded ridge on left valve fits into a broad furrow immediately overlying projection of right valve; a narrow crest above this furrow meets a fine groove on left valve.

MEASUREMENTS: Three excellently preserved specimens give the following dimensions (in mm.):

	l	h	½c	½cfl	gp
1.	9.9	4.6	2.1	3.0	5.2
2.	6.8	3.6	1.7	1.7	3.3
3.	6.8	3.5	1.6	1.7	3.4

½ cfl = convexity at flange
gp = hinge length posterior to beak

TYPES: Holotype: Amer. Mus. Nat. Hist. 27096:1. Paratypes: Amer. Mus. Nat. Hist., Mus. Northern Ariz.

DISCUSSION: This form agrees with the generic characters of *Goniophora* in its dentition, shape of shell, and prominent angular umbonal ridge. Although smaller than most older representatives of the genus, it resembles in size the Pennsylvanian form *G. plicata* Hall, which, however, is distinguished by its two posterior ridges. No other forms are known to range as late as Permian.

OCCURRENCE: Loc. 1, bed 9 (rare, external molds); loc. 2, bed 4 (very rare, external molds); loc. 3 (rare, silicified).

Family MYALINIDAE

Genus *Myalinella* Newell 1942

Myalinella? adunca sp. nov.

Pl. 9, figs. 1, 2

DESCRIPTION: Elongate, oblique, convex mytilids with terminal beaks. Cardinal line straight or very gently arcuate, two-thirds to three-fourths the length of shell; posterior margin curved, meeting posterior part of hinge at an angle of 125°–130°, and rounding rather sharply into antero-ventral margin; antero-ventral margin gently concave along its entire length, strongly so in some specimens, and without anterior lobation. Umbonal ridge prominent but, because of absence of anterior lobation, not well defined; beaks sharp and curved forward.

Shell seemingly smooth; faint concentric rugations very indistinctly visible on interior of shell.

Hinge seemingly edentulous, bearing an elongate nymph below a shallow furrow for support of ligament. Muscle scars and pallial line not visible.

MEASUREMENTS: Five well preserved internal molds have the following dimensions (in mm.):

	l	h	½c	md	valve
1.	18.8	19.2	4.3	22.0	right
2.	14.5	12.6	2.5	15.3	left
3.	13.4	13.1	2.5	15.6	right (holotype)
4.	12.6	12.3	2.8	15.1	right

md = maximum diameter, measured from beak to posterior ventral margin.

TYPES: Holotype: Mus. Northern Ariz. G2.542. Paratypes: Mus. Northern Ariz.

DISCUSSION: This species is referred to the genus *Myalinella* because of lack of anterior lobation. It differs from known species of *Myalinella* in the pronounced curvature of its umbonal ridge and the concavity of its antero-ventral margin.

Though strongly resembling *Promytilus retusus* sp. nov., *Myalinella adunca* differs from that form in a number of characters. The shell is proportionately shorter and less oblique than in *P. retusus* and the umbonal ridge shows a marked curvature. The hinge is short, the beaks are more pointed, and there is no pronounced anterior lobation. In addition, the posterior margin meets the hinge at an angle of 125°–130°; in *P. retusus* the angle is much more obtuse.

OCCURRENCE: Loc. 1, bed 9 (rare, internal molds).

Superfamily ANATINACEA

Family PHOLADELLIDAE

Genus *Allorisma* KING 1844

Allorisma terminale HALL 1852

Pl. 9, figs. 4a–c

Allorisma terminalis HALL, Stansbury's expedition to the Great Salt Lake (1852), p. 413, pl. 2, figs. 4a, b.
Allorisma subcuneata MEEK AND HAYDEN, Acad. Nat. Sci. Philadelphia, Pr. (1858), p. 263.
Allerisma terminale, GIRTY, U. S. Geol. Survey, Bull. 389 (1909), p. 90 (see for synonymy).

DESCRIPTION: Large, thin-shelled, transversely oval pelecypods with hinge equal to slightly more than half the total length. Cardinal margin straight behind beak; anterior margin rounded, projecting in front of beak less than a seventh the length of the shell; posterior margin regularly rounded, meeting cardinal margin without angulation, and curving somewhat less sharply ventrally to merge with ventral margin; ventral margin almost straight, with a gentle sinuosity about a third the distance back from anterior end of shell. Beaks low, anterior, orthogyrate; umbonal ridge lacking; shell strongly convex anteriorly, flattened posteriorly.

Ornamentation of low, irregular concentric rugae and many minute papillae, the latter arranged in irregular radial rows; shell thin, so that rugae are reflected on interior.

Dentition and other internal features unknown.

MEASUREMENTS: Three internal molds have the following dimensions (in mm.):

	l	h	c	a	h/l	a/l
1.	10.0	5.5±	3.8	1.3	.55	.13
2.	9.3	4.8	3.7	1.3	.52	.14
3.	6.0	3.1	2.2	.8	.52	.13

DISCUSSION: From a study of the type specimens of *Allorisma terminale* Hall and *A. subcuneata*

Meek and Hayden, Girty (1903, p. 438) was able to conclude that the two forms, described from the same horizon at the same locality, are conspecific. The type specimen of *A. terminale* is, according to Girty, elongated by compression, and the beaks are thrust far forward.

Apparently there is considerable variation among members of this species, some showing a concave hingeline, others a straight or convex one. The beaks vary in position, lying behind the anterior margin between .14 and .20 of the total length in examples described and figured by Girty, White, and others. In Kaibab specimens they lie rather uniformly .13–.14 of the total length behind the anterior margin, and thus are slightly more anterior than in most other examples. This discrepancy may be due to the fact that the present material consists of internal molds.

In view of the infraspecific variation evident in this species, the constancy of proportions of the three Kaibab specimens is quite remarkable.

OCCURRENCE: Loc. 1, bed 2 (very rare, internal and external molds), bed 9 (generally rare, occurring in groups; internal and external molds).

Allorisma? juvenile

Pl. 9, figs. 3a, b

A single small but perfect specimen cannot be placed in any of the preceding groups and appears to be a juvenile *Allorisma*. It is completely smooth on the exterior, and lacks dentition.

MEASUREMENTS: Length 5.8 mm., height 3.6 mm.

OCCURRENCE: Loc. 3, (one silicified specimen).

Superfamily PLEUROPHORACEA

Family PLEUROPHORIDAE

Genus *Pleurophorus* King 1844

Pleurophorus albequus Beede 1902

Pl. 9, figs. 5a–6b

Pleurophorus sp. BEEDE, Okla. Geol. Survey, 1st. Bien. Rept., Advance Bull. (1902), p. 9, pl. 1, fig. 4.

Pleurophorus? albequus BEEDE, Kans. Univ., Sci. Bull., vol. 4 (1907), p. 160, pl. 6, figs. 8–8e.

Pleurophorus? albequus longus BEEDE, Kans. Univ., Sci. Bull., vol. 4 (1907), p. 162, pl. 6, fig. 9.

Pleurophorus albequus, NEWELL, Geol. Soc. Am., Bull., vol. 51 (1940), p. 298, pl. 3, figs. 1, 4–8, 14, 16–18.

Pleurophorus albequus longus, NEWELL, Geol. Soc. Am., Bull., vol. 51 (1940), p. 300, pl. 3, figs. 2, 3, 15, 19–23.

Pleurophorus albequus, CLIFTON, Jour. Paleont., vol. 16 (1942), p. 693, pl. 101, figs. 8–12.

DESCRIPTION: Equivalved, very inequilateral, elongate pelecypods of medium size; valves moderately convex, sometimes with a broad, poorly defined sulcus extending postero-ventrally from umbones. Cardinal margin very gently arcuate, rounding into sharply curved posterior margin; ventral margin parallel to cardinal margin, straight or gently arcuate, sometimes slightly sinuate at about mid-length, rounding gently into posterior margin and somewhat more strongly into anterior margin; anterior margin projecting only slightly anterior to beaks, arcuate. Beaks small, anterior, almost terminal, prosogyre; umbonal ridge faintly defined.

Ornamentation commonly so faint as to be almost indiscernible, consisting of low radial ridges on posterior portion of valves, and closely spaced rows of fine papillae covering entire shell; anteriorly, the papillae are less definitely aligned and take on appearance of lamellose, wavy corrugations, but on posterior half or ¾ of shell there are distinct tiny sharp papillae arranged in a quincunxial pattern; growth lines irregular, prominent, often rugose, frequently with stronger growth constrictions.

Lunule small, very deep, clearly defined; escutcheon long and very narrow, set off from rest of shell by low angular ridge; deep, narrow ligament groove extending from beak half the length of escutcheon; dentition 1 cardinal tooth in each valve, and 1 lateral tooth in left valve; cardinal tooth of right valve triangular, lying above socket; cardinal tooth of left valve transverse, with triangular base, lying below triangular socket, and bearing on its dorsal surface a tiny secondary socket, presumably to receive an irregularity of cardinal tooth of right valve; lateral tooth of left valve originating at about mid-length and extending posteriorly with slight obliquity, forming with cardinal margin a long, narrow, triangular socket which receives extended margin of right valve. Anterior muscle scar very deep, bounded posteriorly by thick, prominent buttress; posterior muscle scar usually not well defined; a rather large pedal muscle scar forms an arcuate pit on ventral surface of cardinal tooth of left valve, and corresponding pit on right valve is located just below cardinal socket.

Relatively few immature specimens are available, the majority of the specimens being of approximately the same size and apparently mature. No pronounced change in shape, ornamentation, or rate of growth can be observed.

MEASUREMENTS: (in mm.)

	l	h	c	h/l
1.		11.5	7.0	
2.	27.6	11.2	7.0	.41
3.	25	10.2		.41 (mold)
4.	20+	9.4		.47 (mold)
5.	19.7	8.5	6.6	.43
6.	17.2	7.0		.41 (mold)
7.	14.8	6.2		.42 (mold)
8.	13.7	5.8		.42 (mold)
9.	11.0	5.2		.47 (mold)
10.	9.5	4.7	4.0	.49 (mold)
11.	8.1	3.6		.44 (mold)

DISCUSSION: In size, shape, ornamentation, and characters of dentition, this form seems to be identical with forms from the Whitehorse sandstone and Dozier dolomite described by Beede as *P. albequus* and *P. albequus longus*. The latter subspecies, occurring as it does in association with *P. albequus*, seems to be not a true subspecies, but to consist of more fully mature individuals or slightly more elongate variants of the same species. The species has also been recognized from the Blaine and Dog Creek formations of Texas.

OCCURRENCE: Loc. 1, bed 2 (common, external and internal molds), bed 9 (common, external and internal molds); loc. 2, bed 4 (abundant, internal and external molds); loc. 3 (very rare, silicified).

Pleurophorus cf. *P. mexicanus* GIRTY

Internal molds of an elongate, posteriorly contracted pleurophorid are extremely abundant at an unidentified horizon in the Kaibab limestone (Alpha member). They most closely resemble, in both size and shape, Girty's form from the Manzano group (Permian), a species which has also been identified by Clifton from the Permian Blaine and Dog Creek formations of Oklahoma.

MEASUREMENTS: (in mm.)

	l	h	½c	valve
1.	30	14	4.5	left
2.	27	14	5.5	both
3.	27	13.5	4	left
4.	26	13	5	right
5.	25	12	3.5	left
6.	24	11.5	5	right
7.	23	11	3	right
8.	21	11	3	right
9.	20	10	3	left
10.	17	8		left

OCCURRENCE: Loc. 1, bed 9 (rare, external and internal molds). This form occurs abundantly in debris from the excavations at loc. 1, and is thought to have come from beds lower than those measured.

Genus *Rimmyïmina* gen. nov.

Pleurophorus, BITTNER (pars), Abh. der K. K. Geol. Reichsanstalt, Wien, Bd. 18, Heft 2 (1907), p. 156.

DIAGNOSIS: Equivalved, inequilateral, quadrangular to oblong pelecypods with beak anterior but not terminal. Hinge with elongate, narrow escutcheon bearing a fine ligament groove, and small but well defined lunule. Dentition actinodont, with an obtuse, elongate, obliquely oriented cardinal tooth in right valve, and a shallow socket, formed by shelf-like extension of anterior margin, in left valve; left valve with well developed posterior lamellar tooth; right valve with obscure posterior lamellar ridge on interior of shell, possibly representing a tooth.

GENOTYPE: *Rimmyjimina arcula* sp. nov.

DISCUSSION: The shells representing this genus show definite affinity with the genus *Pleurophorus*, but differ too markedly in dentition to be assigned to that genus. *Pleurophorus*, as redefined by J. Bohm (1914), bears a well defined cardinal tooth in each valve, and has in each valve also a deep, clearly defined socket. Triassic forms identified by Bittner as *Pleurophorus curionii* Hauer and *P. curionii* var. *meriani* Parona, appear to have dentition similar to the specimens at hand, and are interpreted as belonging within the new genus.

Licharew defined the Upper Permian genus *Pleurophorina* as having no tooth in the left valve, but his photographs of a squeeze do not convincingly corroborate his definition: the specimen appears to be a true *Pleurophorus* and is not easily confused with the present form.

RANGE: Permian, Kaibab formation; Upper Triassic.

Rimmyïmina arcula sp. nov.

Pl. 9, figs. 7–11b

DESCRIPTION: Small, subquadrate, closed, moderately convex pleurophorids, somewhat expanded posteriorly, with height 0.6–0.7 the length. Cardinal margin gently convex; hinge equal to about ⅔ total length in juveniles, somewhat more in larger shells; anterior margin somewhat lobate, straight but steeply inclined below beak and rounding rather sharply into ventral margin, sometimes forming a point. Ventral margin very gently convex in most individuals, but in many juveniles showing a slight sinus in anterior third; ventral margin curving more strongly posteriorly to meet posterior margin at an obscure angulation; posterior margin regularly

convex, almost vertical, meeting cardinal margin at an obtuse angle. Beak low, anterior but not terminal, prosogyrate; umbonal ridge very obscure, extending from beak to posterior ventral angulation; valves fairly convex, convexity being greatest along umbonal ridge, and shell below umbonal ridge almost flat or, in many juveniles, gently depressed.

Ornamentation lacking; growth lines fine, slightly lamellose, often very distinct, especially on ventral slope; occasional more strongly marked constrictions are evident on some shells.

Hinge arcuate, with a long, narrow escutcheon, finely pointed anteriorly, separated from rest of valve by a rounded ridge; ligament groove thin, extending from beak half to ⅔ the length of cardinal margin; lunule small, oval, depressed, lying almost under beak; dentition actinodont, right valve bearing an obtuse, broadly triangular, low cardinal tooth below beak, and left valve with a shelf-like extension of anterior margin to serve as a socket for it; an elongate posterior lamellar tooth diverges from posterior cardinal margin of left valve, forming with it an elongate triangular socket for reception of extended margin of right valve; in right valve, there is a very slight prominence immediately beneath posterior end of cardinal margin which has the appearance of an undeveloped lateral tooth. Anterior muscle scar pronounced, deeply imbedded beneath a strut-like ridge which extends from antero-lateral surface obliquely upward to inner surface of lunule; posterior muscle impression seemingly somewhat larger than anterior, located close under posterior part of hinge, not strongly impressed; pallial line simple, not strongly impressed.

MEASUREMENTS: (in mm.)

	l	h	½c	g	h/l	c/l	g/l	vent. mgn.	valve
1.	10.2	6.9	2.75	8.5	.68	.54	.83	straight	(holotype)
2.	6.8	4.6	1.95	5.6	.68	.57	.82	straight	right
3.	6.7	4.2	1.7+	5.3	.63	.51	.81	straight	right
4.	5.7	3.9	1.55	4.4	.68	.54	.77	sinuate	right
5.	5.4	3.8	1.4	4.3	.70	.52	.80	straight	right
6.	5.4	3.7	1.4	3.7	.69	.52	.69	sinuate	left
7.	5.3	3.7	1.2	4.1	.70	.45	.77	straight	left
8.	5.1	3.4	1.3	3.6	.67	.51	.71	straight	left
9.	4.9	3.3	1.3	3.6+	.67	.53	.73	sinuate	left
10.	4.9	3.1	1.3	3.3	.63	.53	.73	straight	right
11.	4.8	3.1	1.25	3.3	.65	.52	.69	sinuate	left
12.	4.7	3.1	1.3	3.5	.66	.55	.74	straight	left
13.	4.7	3.0	1.2	3.2	.64	.50	.68	sinuate	right
14.	4.6	3.0	1.3	3.7	.65	.57	.80	straight	right
15.	4.6	2.8	1.15	3.2	.61	.50	.70	straight	right
16.	4.5+	3.1	1.1	3.4	.69	.49	.76	straight	left
17.	4.4	2.8	1.1	3.3	.64	.50	.75	straight	left
18.	3.6	2.4		2.7	.67		.75	sinuate?	right
19.	3.5	2.1	.95	2.4	.60	.54	.69	sinuate?	left
20.	2.7	1.7	.7	1.9	.63	.52	.70	straight	left
21.	2.5	1.6	.6	1.7	.64	.48	.68	straight	right

TYPES: Holotype: Mus. Northern Ariz. G2.541. Paratypes: Mus. Northern Ariz., Amer. Mus. Nat. Hi st

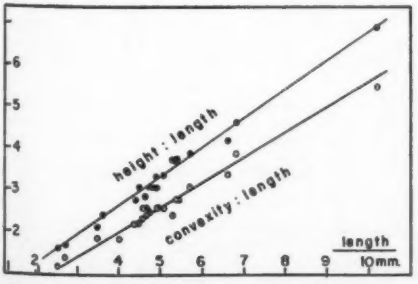

FIGURE 14.—RELATION OF HEIGHT AND CONVEXITY TO LENGTH IN *Rimmyjimina arcula*

DISCUSSION: Although in proportions of length, width, and thickness this form appears to remain about the same during ontogeny, several changes in shell form may be noted. In the very smallest shells the ventral margin is straight for much of its length. In shells about 4.5–5.5 mm. long there is commonly a gentle sulcus developed anterior to the umbonal ridge, forming a sinus in the margin. With further growth the sinuosity disappears, so that when the shell is about 6.5 mm. long, the ventral margin is gently convex.

A slight trend is seen toward relative elongation of the cardinal margin with growth, the posterior margin becoming straightened simultaneously. Ad-

ditional material is needed to show this, however, as the present collection has few shells between 6 and 10 mm. long. The single shell over 10 mm. long is decidedly flattened posteriorly.

OCCURRENCE: Loc. 3 (juveniles common, adults rare, silicified).

Superfamily ASTARTACEA

Family ASTARTIDAE?

Genus ***Kaibabella*** gen. nov.

DIAGNOSIS: Equivalved, almost equilateral, oval pelecypods having an arcuate hinge with a small, poorly defined lunule and a long, narrow escutcheon. Dentition preheterodont (?), with 2 large, triangular cardinal teeth in each valve, those in left valve anterior to those in right valve; without lateral teeth. A rudimentary third tooth may be present below the ligamental furrow.

GENOTYPE: *Kaibabella curvilenata* sp. nov.

DISCUSSION: This genus does not show the lateral teeth evident on the genotype of *Astarte*, and present in *Astartella*. *Astartila*, as now understood, lacks teeth altogether and has a much longer external ligament than does the present form. The genus *Pachydomus* from the Permian of Australia is probably also related. It is defined as having "one or two (?) large teeth in each valve," the one in the left valve being the largest, but no illustrations have been presented of its dentition. Australian species are all many times larger than the Kaibab form, and much more convex.

RANGE: Permian, Kaibab formation.

Kaibabella curvilenata sp. nov.

Pl. 10, figs. 1a–4c

DESCRIPTION: Small, roundly triangular or ovate pelecypods, slightly longer than wide, with convexity about half the length in adults, somewhat less in juveniles. Anterior margin almost smoothly curved, but forming a slight angle about halfway down and rounding smoothly into ventral margin; posterior margin very slightly curved, often with a slight angulation ⅔ of the distance to posterior extremity, rounding sharply into ventral margin at posterior extremity; ventral margin smoothly curving; beaks small, pointed, probably almost in contact when shell is closed; shell regularly and smoothly arched except for a low, obscure umbonal ridge limiting a slightly flattened posterior area.

Ornamentation fairly strong, rounded concentric undulations, 9 in 5 mm. near ventral margin of largest specimen, but much more closely spaced and often obscure near umbo and on small specimens.

Lunule short and not strongly defined except near beak; escutcheon long, narrow, very poorly defined, with a short, arcuate ligamental furrow starting at beak and extending posteriorly less than half the length of escutcheon. Dentition preheterodont (?) with 2 large, triangular cardinal teeth in each valve, those in left valve lying anterior to 2 triangular, vertically walled sockets and those in right valve lying posterior to sockets; in left valve, posterior tooth is the more prominent; in right valve, anterior one is larger; anterior tooth of left valve continuous with anterior margin of shell; in both valves the ligamental furrow limiting a very rudimentary third tooth; dentition supported by a strong, thick, rounded shelf. Anterior and posterior adductor scars about equal, each slightly impressed, both located fairly near beak. Pallial line simple, but not distinct. Anterior pedal muscle scar fairly deep, lying close under lunule, above anterior adductor impression, on rounded shelf which supports teeth; posterior pedal impression very deep, lying far under shelf.

No change in proportions of length or width during ontogeny can be seen, but there is a slight increase in convexity as shell becomes larger.

MEASUREMENTS: (in mm.)

	l	h	c	h/l	c/l
1.	13.9	11.5	7.2	.83	.52 (holotype)
2.	12.7	10.6	6.0	.83	.47
3.	10.2	8.0	4.0	.78	.39
4.	10.0	8.3	5.0	.83	.50
5.	7.9	6.4	3.5	.81	.44
6.	7.4	5.9	3.2	.80	.43
7.	7.2	6.4	3.4	.89	.47
8.	6.7	5.8	2.5	.86	.37
9.	6.1	5.2	2.2	.85	.36
10.	5.4	4.5	2.0	.83	.37
11.	4.4	3.8	1.5	.86	.34
12.	4.0	3.6	1.6	.90	.40
13.	3.7	3.2	1.4	.86	.38

TYPES: Holotype: Mus. Northern Ariz. G2.1748. Paratypes: Mus. Northern Ariz., Amer. Mus. Nat. Hist., Grand Canyon Nat. Park museum.

OCCURRENCE: Loc. 1, bed 9 (common, external and internal molds); loc. 2, bed 4 (very rare, external and internal molds); loc. 3 (rare, silicified).

Family ASTARTIDAE

Genus ***Astartella*** Hall 1858

Astartella subquadrata Girty

Pl. 10, figs. 5–15

Astartella subquadrata GIRTY, U. S. Geol. Survey, Bull. 389 (1909), p. 94, pl. 10, figs. 10–13.
Astartella subquadrata, CLIFTON, Jour. Paleont., vol. 16 (1942), p. 693.

DESCRIPTION: Small, thick-shelled, subquadrate pelecypods, slightly longer than high, with thickness

somewhat more than half the length. Cardinal margin and ventral margin gently curved, more or less distinctly contracting posteriorly; posterior outline nearly perpendicular to cardinal and ventral margins, and gently convex, rounding into ventral margin but meeting cardinal one in an obscure angle; anterior outline concave below beak, extending downward and somewhat forward for about two-thirds or three-fourths length of shell, meeting upward-curving anterior end of ventral outline usually in a rather distinct angle; beak flattened; no appreciable umbonal ridge.

Ornamentation of regular concentric lamellae, varying in number according to size of shell, the distance between lamellae increasing regularly from beak to margin; lamellae about 5 per mm. next to umbo, 2 per mm. near ventral margin of large specimens; lamellae thus about 9 in number in specimens under 3 mm. in length, at least 15 in number in those of 16 mm.

Hinge structure and dentition typically astartellid; concave lunule anterior to beak; cardinal margin bearing a well-marked escutcheon; each valve with a strong cardinal tooth, that of left valve being posterior to a deep triangular socket, that in right valve being anterior to socket; along cardinal margin of left valve a trench-like depression receives the sharply angular edge of right valve, and a similar groove anterior to beak of right valve corresponds with angular and somewhat extended edge of left valve. Anterior muscle scar impressed, especially at its posterior margin; other muscle scars not evident.

No change in proportions during ontogeny is evident.

MEASUREMENTS: An abundance of excellently preserved specimens permitted a large number of measurements to be made. Variability in measurement of angles is unavoidable because of difficulty in making measurements in these shells. Dimensions in mm.:

	l	h	½c	g	h/l	c/l	g/l
1.	7.4	6.2	2.4		.84	.65	
2.	7.3	6.4	2.4	5.4	.88	.66	.74
3.	7.0	6.0	2.6		.86	.66	
4.	6.9	6.2	2.2	5.0	.90	.64	.73
5.	6.9	5.7	2.2		.83	.64	
6.	6.9	5.6	2.0		.81	.58	
7.	6.7	5.9	2.1		.88	.63	
8.	6.7	5.9	2.2	4.8	.88	.66	.72
9.	6.7	5.8	2.1		.87	.64	
10.	6.6	5.9	2.0	4.6	.90	.70	.61
11.	6.5	5.6	2.4		.86	.74	
12.	6.5	5.3	2.2		.82	.68	
13.	6.5	5.0	2.0	4.0	.77	.62	.62
14.	6.5	5.3	1.8		.82	.55	
15.	6.4	5.5	1.9	4.4	.86	.59	.69
16.	6.3	5.4	2.0	4.1	.86	.63	.65
17.	6.3	5.2	2.1	4.4	.83	.67	.70
18.	6.2	5.4	2.2		.87	.71	
19.	6.2	5.3	2.0	4.4	.86	.64	.71
20.	6.1	5.4	2.0	4.3	.89	.66	.70
21.	6.0	5.1	1.9		.85	.64	
22.	6.0	5.1	2.0		.85	.67	
23.	6.0	5.0	1.8	3.8	.84	.60	.63
24.	5.8	5.2	1.9	4.1	.90	.66	.71
25.	5.8	5.2	1.8	4.0	.90	.62	.69
26.	5.8	5.0	1.8	4.0	.86	.62	.69
27.	5.8	5.0	1.7	4.0	.86	.59	.69
28.	5.6	4.7	1.7		.84	.61	
29.	5.3	4.9	1.8		.93	.68	
30.	5.3	4.6	1.7		.87	.64	
31.	5.3	4.3	1.6	3.4	.81	.61	.64
32.	5.2	4.3	1.6		.83	.62	
33.	5.1	4.5	1.7		.89	.67	
34.	5.0	4.4	1.6		.88	.64	
35.	5.0	4.4	1.7	3.5	.88	.68	.70
36.	5.0	4.1	1.4	3.2	.82	.56	.64
37.	4.8	4.4	1.4	3.5	.92	.58	.73
38.	4.8	4.0	1.6		.83	.67	
39.	4.8	3.8	1.4	3.4	.79	.58	.71
40.	4.7	4.0	1.5		.85	.64	
41.	4.7	4.0	1.5	2.9	.85	.64	.58
42.	4.6	4.2	1.6		.91	.69	
43.	4.5	4.0	1.4		.89	.62	
44.	4.4	4.0	1.4		.91	.64	
45.	4.4	4.0	1.2	3.0	.91	.55	.68
46.	4.3	3.6	1.3	2.9	.84	.60	.67
47.	4.2	3.4	1.2		.81	.57	
48.	4.2	3.1	1.2		.74	.57	
49.	4.0	3.6	1.4		.90	.70	
50.	4.0	3.5	1.2		.87	.60	
51.	4.0	3.4	1.1	2.8	.85	.55	.70
52.	3.9	3.5	1.3	2.7	.90	.67	.69
53.	3.8	3.2	1.0		.84	.53	
54.	3.8	3.2	1.2		.84	.63	
55.	3.8	3.5	1.1	2.6	.92	.58	.68
56.	3.8	3.4	1.3	2.6	.89	.68	.68
57.	3.6	3.0	1.0		.83	.55	
58.	3.2	2.8	0.9	2.2	.86	.56	.69
59.	3.0	2.8	1.0	1.9	.93	.67	.63
60.	2.9	2.6	0.8	2.1	.90	.55	.72

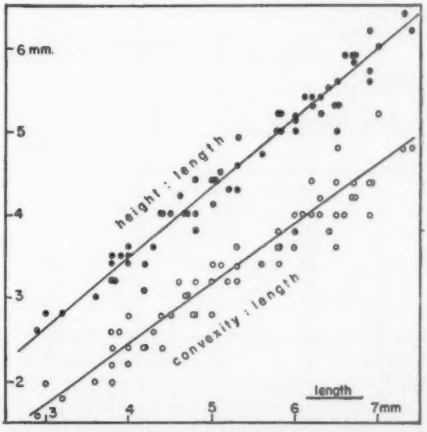

FIGURE 15.—RELATION OF HEIGHT AND CONVEXITY TO LENGTH IN *Astartella subquadrata*

DISCUSSION: This species may be far more widespread than recorded observations indicate. Described by Girty from the Manzano group (Permian), and recorded by Clifton from the Blaine and Dog Creek formations, it also occurs in the Word limestone no. 1 of the Texas Permian section. Several European and Asiatic forms appear to be similar to Girty's species but are too poorly figured to make synonymy certain.

OCCURRENCE: Loc. 1, beds 2 and 9 (abundant, external and internal molds); loc. 3 (abundant, silicified).

Superfamily GRAMMYSIACEA

Family SOLENOPSIDAE

Genus *Sanguinolites* McCoy 1844

Sanguinolites? sp.

Pl. 10, figs. 16, 17

DESCRIPTION: Elongate, equivalved, inequilateral pelecypods of flattened cylindrical form, slightly gaping posteriorly. Hingeline straight or slightly concave upward; anterior margin gently concave in front of beaks, then curving sharply down and rounding into gently curving, slightly sinuate ventral margin; posterior margin arcuate but appearing slightly truncate, as it rounds suddenly into ventral margin. Beaks low, rather flat, located about a third of distance from anterior margin; umbonal ridge low but distinct, dividing posterior portion of shell into an elongate triangular area which is bisected longitudinally by a second low ridge.

Ornamentation coarse, irregular growth lines giving shell the appearance of being concentrically wrinkled.

Hinge characters not known; shells appear edentulous.

MEASUREMENTS: (in mm.)

	l	h	½c	valve
1.	40	16.5	5	right
2.	36	12	2.5	left
3.	35	13.5	3.5	right
4.	34.	15	5	left
5.	32	13	3	right
6.	31	14	3.5	right
7.	25+	11	3.5	left
8.	22	8	2	right
9.	20	7	1.5	right
10.	17	6.5	1.5	left
11.	15	7.5	1.5	right
12.	14	5	1	left
13.	10	4	1	left

DISCUSSION: This form most closely resembles members of the genus *Sanguinolites*, but cannot definitely be assigned to that or any related genus until the confusion surrounding definition of the genera has been clarified. The posterior triangular area, set off by the umbonal ridge, recalls such forms as *Allorisma? geinitzi* (Meek), *A.? costatum* Meek and Worthen, and *Pleurophorus subcostatus* Meek and Worthen. In none of those species is the dentition well known, and it is likely that they are all more closely related generically than has heretofore been indicated.

OCCURRENCE: Loc. 1, bed 9 (common, external and internal molds); loc. 2, bed 4 (very rare, external molds of immature individuals).

Genus *Alula* Girty 1912

Alula gilberti (White)

Pl. 10, fig. 18

Allerisma gilberti WHITE, U. S. Geol. and Geog. p. 137, Survey Terr., Rept. for 1878, pt. 1 (1883), pl. 33, figs. 9a, b.
Alula gilberti?, GIRTY, N. Y. Acad. Sci., Ann., vol. 22 (1912), p. 5, pl. 1, fig. 6.

A single small but complete internal mold of a right valve shows the characteristic shape, as well as the impression of the chondrophore (identified by Girty as a cardinal tooth) and elongate posterior lateral teeth (possibly an elongate nymph) of the genus *Alula*.

The mold is elongate, with the hingeline long and gently arcuate upward and extending almost the entire length of the valve. The anterior margin is convex and rounds smoothly into the long, arcuate ventral margin. Posteriorly the rostrum is apparently truncate and open. The beak is moderately well developed.

The impression shows that high, platelike posterior lateral ridges, the edges of a linear nymph, extend along the anterior two-thirds of the cardinal margin. An impression below the beaks suggests a triangular chondrophore.

MEASUREMENTS: Length 10.6 mm.; height 4.2 mm.; convexity of one valve 1.0 mm.

DISCUSSION: This specimen is easily identified as *A. gilberti*, first described by White from the Kaibab formation south of Pipe Springs, Arizona, and also recognized by Girty in the Lykins formation (Permian) of Colorado. It is distinguished from *Alula squamulifera* Girty, also from the Lykins formation, by its shorter length and lack of a strong umbonal ridge.

OCCURRENCE: Loc. 1, bed 9? (very rare, internal mold).

Family CARDIOMORPHIDAE

Genus *Edmondia* Koninck 1841

Edmondia sp.

Pl. 7, fig. 16

Internal molds of edentulous pelecypods of medium size and somewhat ovate outline show evidence of the concentric ornamentation which characterizes the genus *Edmondia*. The form is rather less elongate and more quadrangular than Girty's species *E.? bellula* and *E.? phosphatica*, though it most closely resembles the latter. Specimens are much larger than *E. minuta* Stauffer and Schroyer, and smaller and more quadrate than *E. gibbosa* Swallow. From all these Permian forms they can easily be distinguished, and probably a new species is represented. More complete material is necessary for complete description, however.

MEASUREMENTS: (in mm.)

	l	h	½c
1.	16+	12	4
2.	15.5	11.5	4.5

OCCURRENCE: Loc. 1, bed 9? (rare, internal molds).

Superfamily SOLEMYACEA

Family SOLEMYACIDAE

Genus *Solemya* Lamarck 1818

Solemya parallella (Beede and Rogers) 1899

Solenomya parallella BEEDE AND ROGERS, Kans. Univ. Quart., vol. 8 (1899), p. 131, pl. 34, fig. 1.

DESCRIPTION: Elongate-cylindrical shells, seemingly gaping at both ends, with straight, parallel cardinal and ventral margins and rounded anterior and posterior margins. Beaks not elevated, located a fourth or fifth the length of shell from anterior end.

Ornamentation low, wide, flat radiating costae separated by narrow concave striae; costae sometimes marked with very shallow striations.

Hinge and dentition not known.

MEASUREMENTS: Three fragmentary specimens of about the same size show the following reconstructed dimensions (in mm.):

	l	h	c
1.	47+	16	10.5
2.	45+	15+	13
3.	43+		11

DISCUSSION: These specimens differ from most species of *Solemya* in their unusual radial ornamentation, and seem to be conspecific with *S. parallella*, described by Beede and Rogers from the Middle Pennsylvanian of Kansas.

OCCURRENCE: Loc. 1, bed 9 (rare, external and internal molds); loc. 3 (rare, silicified).

Class SCAPHOPODA

Family DENTALIIDAE

Genus *Plagioglypta* Pilsbry 1898

Plagioglypta canna (White) 1874

Dentalium canna WHITE, U. S. Geog. Geol. Survey W. 100th Mer. (1874), p. 23.
Plagioglypta canna, GIRTY, U. S. Geol. Survey, Prof. Paper 16 (1903), p. 452.
Plagioglypta canna, BRANSON, Univ. Missouri Studies, vol. 5 (1930), p. 58 (see for synonymy), pl. 15, fig. 6.

DESCRIPTION: Subcylindrical, gradually tapering, very gently curved scaphopods, with thick shells lacking ornamentation but showing irregular transverse growth striae.

MEASUREMENTS: No complete specimens were collected, but several fragments show the following dimensions (in mm.):

	l	ds	dl
1.	87	2.0	8.3
2.	52	2.0	6.0
3.	50	4.0	8.0
4.	25	1.8	3.6
5.	2	1.8	4.0

ds = diameter at small end
dl = diameter at large end

The shell is about 1 mm. thick at the large end of broken fragments, but thins rapidly toward the aperture of unbroken specimens.

OCCURRENCE: Loc. 1, bed 9 (common, internal and external molds); loc. 2, bed 4 (abundant, internal and external molds); loc. 3 (abundant, silicified).

ECHINODERMATA

Class CRINOIDEA

Crinoid plates

Pl. 5, figs. 19a–29

Numerous crinoid brachial plates and a few tiny columnals were collected from locality 3. The arm plates range in diameter from 2 to 12 mm., large ones being about 3 mm. in maximum thickness but usually thinner on one side than the other. They

are almost circular in plan and bear an ambulacral notch on one side; occasional plates are doubly notched. The muscle pattern is distinctive, consisting of 3 tiny central ridges, the center one the longest, and a marginal depression on one surface of the plate, and a transverse or obliquely transverse ridge on the other side. The ambulacral notch is bounded on one side by strong ridges, on the other by depressions.

OCCURRENCE: Loc. 3 (common, silicified).

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MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, MAY 25, 1949.

PLATES 1–10

PLATE 1.—GASTROPODS

Page

Euphemites aequisulcatus sp. nov. 113

1a–c. Holotype, a specimen from loc. 3; apertural, lateral, and adapertural views, × 2.

Bellerophon deflectus sp. nov. 111

2a–c. Topotype, a juvenile specimen from loc. 3; apertural, adapertural, and lateral views, × 1.

3a, b. Holotype, a specimen from loc. 3; adapertural and lateral views, × 1.

4. Topotype, a very young specimen showing juvenile shape; apertural view, × 4.

5a, b. Topotype, a large specimen; oblique-lateral view to show shape of callus, apertural view, × 1.

GASTROPODS

GASTROPODS

PLATE 2.—GASTROPODS

Page

Retispira undulata sp. nov. 113

1a, b. Rubber squeeze of holotype, an external mold from loc. 2, bed 4; apertural and lateral views, × 2.

Euphemites sp. 113

2. Specimen from loc. 3; apertural view, × 1.

Warthia sp. 114

3a, b. Specimen from loc. 3; apertural and lateral views, × 3.

4. Larger specimen from loc. 3, showing sinus in broken outer lip; oblique-apertural view, × 2.

Anomias franciscanus sp. nov. 114

5a–c. Holotype, a specimen from loc. 3; apertural, basal, and adapertural views, × 4.

6. Topotype, an eroded specimen; apertural view, × 4.

Glabrocingulum laeviliratum sp. nov. 117

7. Topotype, a very small specimen from loc. 3, showing nucleus; top view, × 10.

8a, b. Topotype, showing outer lip and selenizonal notch; lateral and apertural views × 4.

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1c
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3b
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4b
5b
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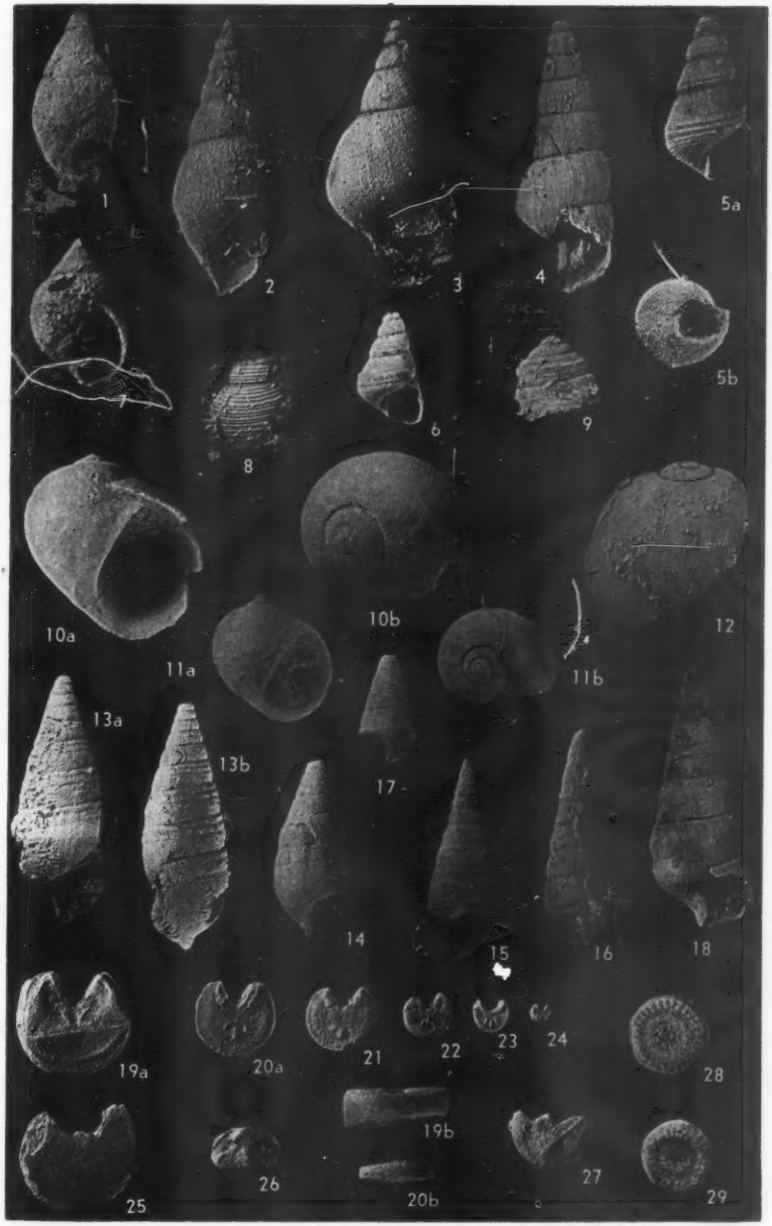

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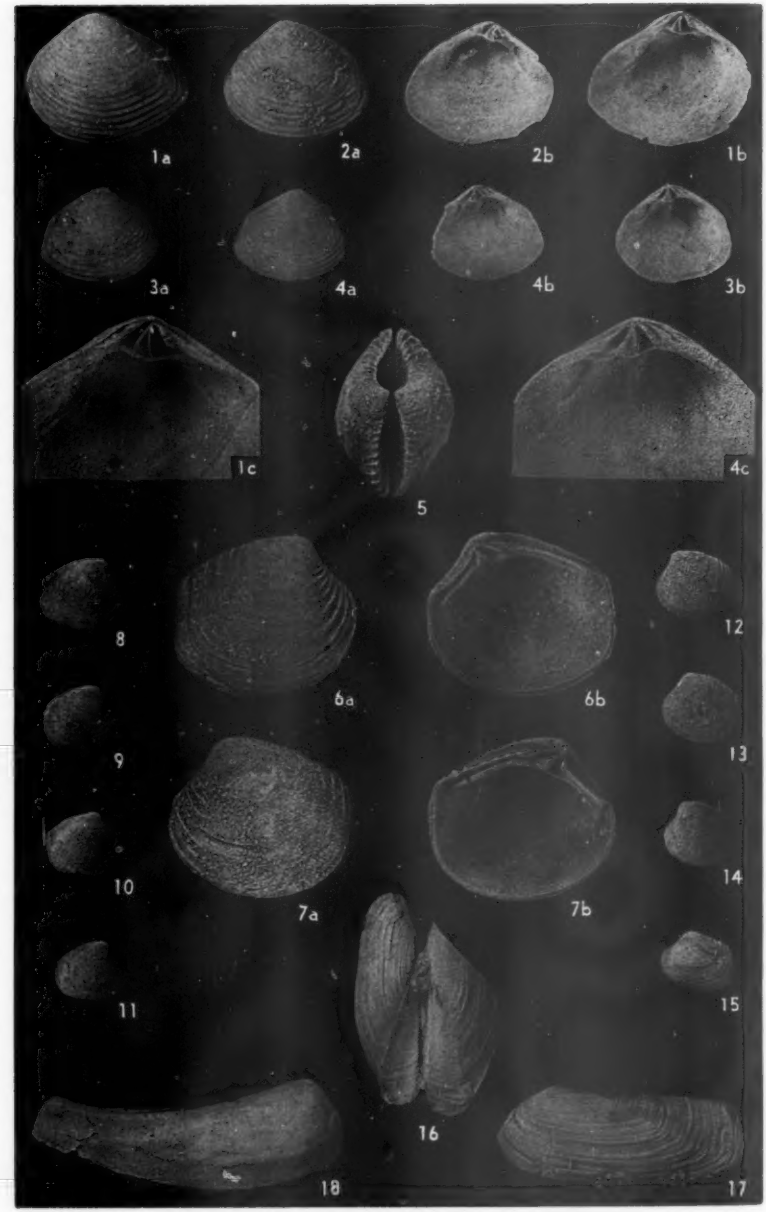
PELECYPODS



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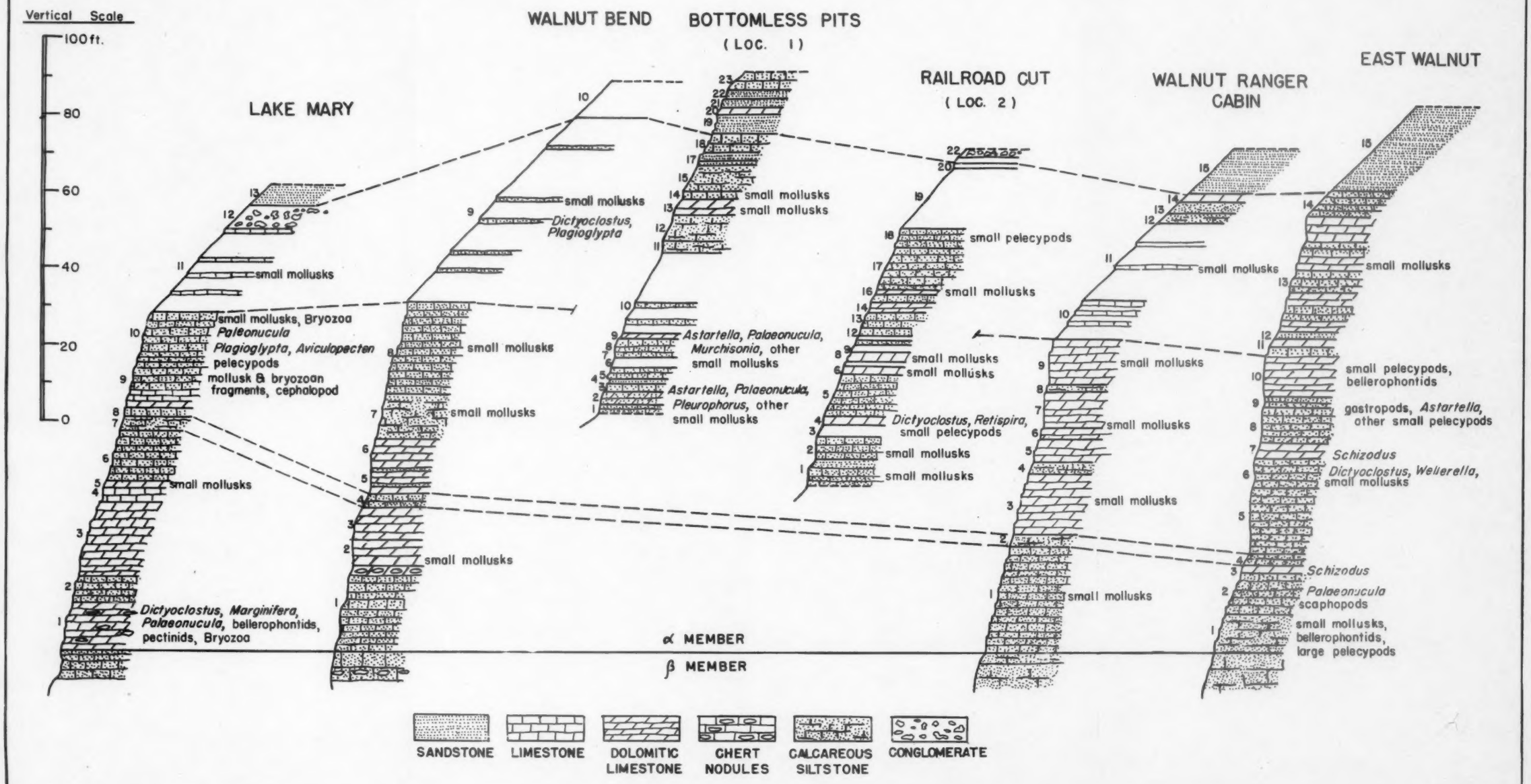

STRATIGRAPHIC SECTIONS OF THE ALPHA MEMBER OF THE KAIBAB FORMATION, IN THE WALNUT CANYON REGION

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 63, PP. 167-224 FEBRUARY 1952

CAROLINA BAYS AND THEIR ORIGIN

BY W. F. PROUTY[1]

ABSTRACT

The Carolina Bays have a known distribution along the Atlantic Coastal Plain from northeast Florida to southeast New Jersey. Estimates based on actual counts in limited regions indicate a conservative figure of half a million bays in the entire area. Local areas show over 50 per cent coverage by bays.

Statistical studies of orientation show a greater divergence of smaller bays from the mean than of larger bays. Smaller bays also show greater variation in ellipticity than do larger bays. Both facts are most satisfactorily explained by the meteoritic theory of origin. Multiple and "heart-shaped" bays overlap in patterns explained most logically by the impact of tandem meteorites, some likely explosive in nature. The probable mechanics of such phenomena is illustrated. Study of near-coast bays indicate that the bays are younger than the youngest Pleistocene terrace and some of the Coastal Plain drainage and older than at least one of the more recent marine transgressions.

Magnetometer studies of 26 different bays all indicate associated spot highs, with no definite highs observed that are not readily associated with some bay.

Laboratory experiments with projectiles involving simulated Coastal Plain conditions duplicate remarkably the cross-section and rim characteristics of the Carolina Bays and strengthen the meteoritic theory.

Although the meteoritic theory in general is indicated by all critical analyses of the bays, a modified meteoritic theory (air-shock wave) is offered to better explain additional data.

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[1] W. F. Prouty passed away June 27, 1949. The article was complete with the exception of the abstract, summary, and conclusions, and the selection and arrangement of a few illustrations which was done by C. E. Prouty, University of Pittsburgh.

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Acknowledgments

It would be impossible to acknowledge all the aid received in this work during the past 14 years. The original field work was initiated by a personal grant of $500 from the Rockefeller Foundation for Research in Pure Science which assisted in the purchase of instruments and defrayed much of the first season's field expenses for a party of three, consisting of G. R. MacCarthy, J. A. Alexander, an advanced student in geology, and myself. In 1937, a grant-in-aid of $1000 was received from the Geological Society of America for intensive study of the bays, including a detailed magnetometer survey of a chosen area in South Carolina, which has one large and several small bays. In this work two magnetometers and

two telescopic alidade and plane table units were employed. Six graduate and advanced geology students from the University of North Carolina: H. W. Straley, W. A. White, T. D. Lance, J. B. Hunter, Grover Murray, and Harry LeGrande, assisted in making the scientific observations. Three small grants from the Smith Fund of the University of North Carolina and a grant from the Carnegie Research Fund for $275 assisted in the purchase of aerial photographs of portions of the bay country, for part of the travelling expenses to Washington, Raleigh and Atlanta, for intensive study of the aerial photographs of the Carolina Bays and the entire Atlantic and Gulf Coastal Plain and bordering areas, also for special field investigation in the Wilmington, North Carolina, area and for assistance in preparing the manuscript.

I am grateful to F. A. Melton for the loan of numerous aerial photographs of portions of the Atlantic Coastal Plain and Gulf regions and for helpful comments regarding work on the bay problem and reviewing the manuscript; to Murray F. Buell for furnishing me with depth of the peat deposits and bottom samples from Jerome Bay, Bladen County, North Carolina; to B. W. Wells for valuable information concerning the flora of the bays and a conducted tour of Blythe Bay, near Wilmington, North Carolina; to G. R. MacCarthy for taking charge of much of the early magnetometer work; to H. W. Straley for supervising the magnetometer survey in the Syracuse Bay area; to Bob Montgomery for his help in locating and identifying some of the bays in the Myrtle Beach Area; to L. C. Glenn, Willard Berry, J. W. Huddle, R. A. Edwards, and C. E. Prouty for accompanying me on cross-section of two small bays along the inland waterway near Myrtle Beach and for their friendly comments; to W. C. Coker for interesting me in the elliptical bays of South Carolina even before the publication of the paper by Melton and Schriever in 1933; to my son W. W. Prouty, for aiding me in visiting many of the bays in the Carolinas; to the late Douglas Johnson for his constant helpful interest in the study of the bays and for numerous letters and joint field trip to several bays in North Carolina; to Stephen Taber and L. L. Smith for discussions and a field trip together to see solution depressions along the inner edge of the Atlantic Coastal Plain; to my colleagues in the University of North Carolina and to numerous audiences and scientific societies for questions and suggestions; to J. C. McCampbell for his thesis study of the bays in the Sessoms Bay area of Bladen County, North Carolina; to Captain Messler for photographs of several bays in Georgia; to J. Hoover Mackin for slides showing lakes near Sarasota, Florida, developed by solution along joint planes in limestone; to Grover S. Plew of the Photographic Division of the A. A. A. in Washington and his staff for their courtesy and great help in making available to me for study thousands of mosaic sheets covering the entire area of the bay country in the Atlantic Coastal Plain and assisting me in getting data for the distribution map of the bays; to the Coast and Geodetic Survey for charts along the Inland Waterway in South Carolina; to the North Carolina office of the A. A. A. at Raleigh for assistance in the study of aerial photographs of the North Carolina Coastal Plain; to the Aerial Photographic Division of the North Carolina State Highway Department for making available to me maps and elevations of the Wilmington area; and to many others who have assisted me in the study of the Carolina Bays.

I wish to express my gratitude to Roy Ingram for plotting the numerous bays on the North Carolina portion of the distribution map of bays published in this report (Pl. 1). I am further indebted to Mrs. R. A. Edwards, Mrs. L. O. Katsoff, Miss Betty Grable, and Mrs. W. B. Cobb for help in preparing the manuscript, and to S. L. Blanton, Jr. for reading and suggesting changes in the manuscript.

Introduction

The terms "bay" and "pocosin" as generally used in the Atlantic Coastal Plain refer to an area usually overgrown with swamp vegetation and underlain by peat deposits. In some areas shallow lakes, with peat-filled border swamps, are also classified as bays.

A large percentage of these bays are nearly elliptical, have approximately the same elongation direction in any given area, are depressed below the general level of the ground, and have well defined sand-rims which rise above the general level of the area. Such elliptical, sand-rimmed bays are now generally spoken of as

the Carolina Bays because of their greater abundance in the two Carolinas, although there is a very sparse and irregular occurrence in the extreme distribution areas, as far south as northeast Florida and as far north as New Jersey (Pl. 1).

In this Coastal Plain area occur hundreds of thousands of these elliptical, sand-rimmed, and oriented depressions. The Carolina Bays have attracted world-wide attention during the past decade or so. Many articles, both scientific and popular, have been written about them, and there is still a great difference of opinion regarding their origin. In the northeastern area of their occurrence, the few bays found have their axial elongation a little to the east of southeast. Southwestwardly, the direction of axial elongation turns gradually clockwise through southeast to a little east of south in central Georgia. There is great variation in the size of the bays—from a few hundred feet to about 7 miles—and also a slight local variation in the direction of elongation of the bays and in their ellipticity. The sand rims are usually best developed along the southeast side. The bays appear to be of about the same age and, seemingly, are independent of topography and rock character.

Michael Toumey (1848), the first State Geologist of South Carolina, was apparently the first scientist to call attention in scientific writing to these peculiar rimmed depressions. The first scientific description was by Dr. L. C. Glenn (1895). Two small depressions of Carolina Bay type, near Darlington, South Carolina, were described and their possible origin suggested. No further published scientific notice was taken of these peculiar land forms until aerial photographs of the Myrtle Beach Estate were studied by Dr. F. A. Melton of the University of Oklahoma. An article by Melton and Schriever (1933), claiming a meteoritic origin of the bays, aroused world wide attention and started intensive investigation which has resulted in varying conclusions as to the probable origin of the bays.

The writer supports the meteoritic theory with revisions, hereinafter explained. Other investigators strenuously advocate origins including: (1) solution; (2) wind and current action; (3) submarine scour and later wind action; (4) artesian springs and ground-water action; (5) earth rotation aided by currents and wind; (6) multiple origin theory, combining 1, 2, and 4; and (7) activity of shoals of fish about fresh-water submarine springs on the Continental Shelf. These theories will be discussed in later chapters.

The conclusions reached in this publication are based upon extensive geological and geophysical investigations in many parts of the Carolina Bay country since 1933. A thorough study of aerial photographs of the entire area and of bordering areas has been of very great assistance, as have also experiments in the formation of elliptical rimmed depressions through the use of high-velocity projectiles.

Different Theories of Origin of Bays

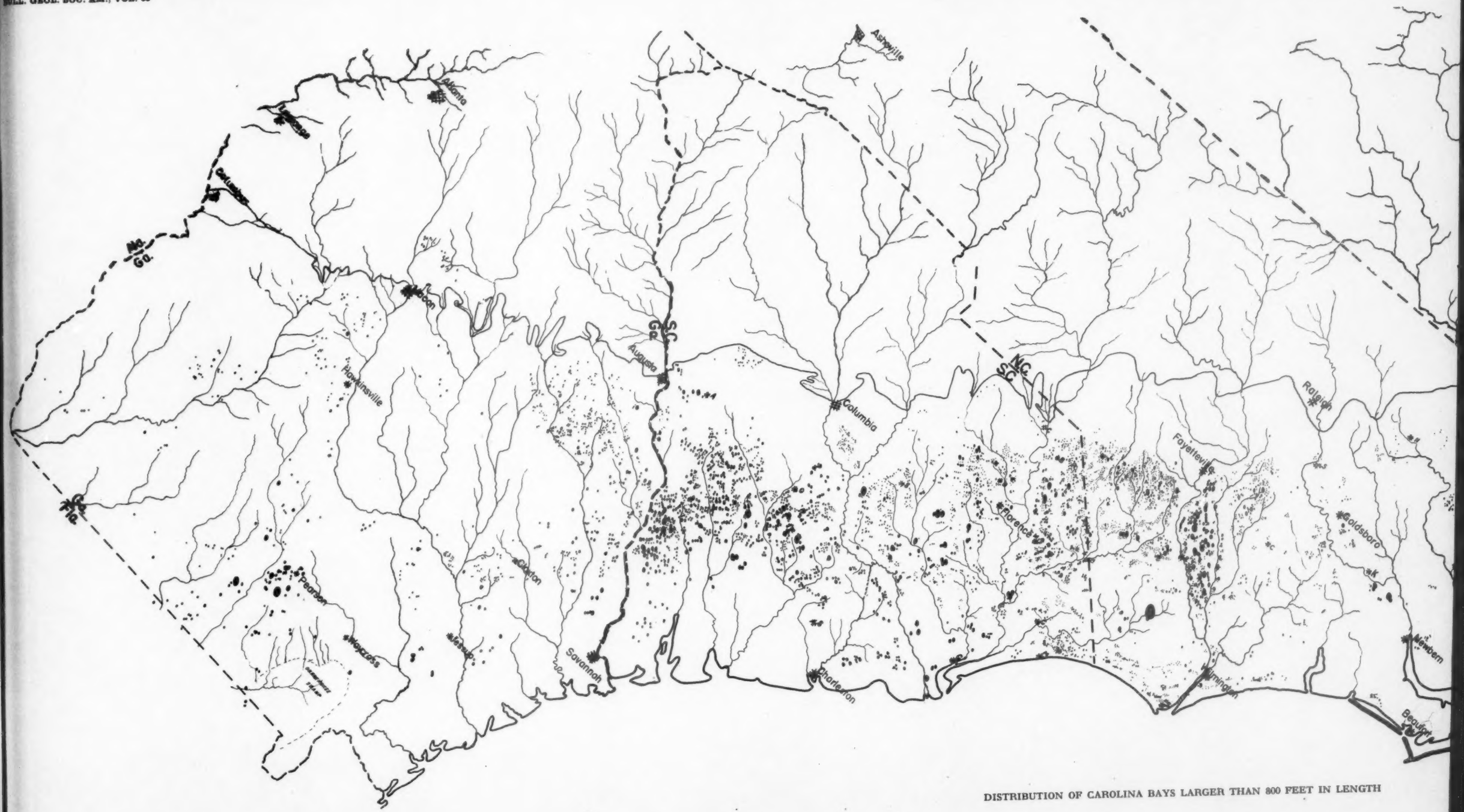
Origin by Terrestrial Forces

When Michael Toumey (1848), State Geologist of South Carolina, spoke of circular bays in Barnwell and Orangeburg counties and other parts of South Carolina, he probably referred to some of the elliptical bays which we now designate "Carolina Bays." He thought (theory 1) these circular lakes were formed by the action of springs rising to the surface of a sandy plain, a mode of origin suggestive of, but not the same as, the Artesian Spring theory developed later by Douglas Johnson.

Glenn (1895) described two small bays near Darlington, South Carolina and suggested two possible modes of origin: (theory 2) that the bays were formed by the building of sand bars, by wind and wave, across the mouths of shallow coastal embayments; and (theory 3) that the bays might have been formed as depressions enclosed by giant sand ripples. Later study has shown that most bays are not associated with such conditions as an embayed coast or beach ridges, but where they are thus associated the bays cut across the beach ridges or sand ripples, proving that the ridges or ripples are older than the bays.

Melton (1934) felt that if the meteoritic theory should be found untenable, which he did not contemplate, his next choice would be (theory 4) formation by submarine scour by eddies, currents or undertow.

There are many bays near certain areas of the coast which must either have been formed in the shallow sea or later flooded temporarily



DISTRIBUTION OF CAROLINA BAYS LARGER THAN 800 FEET IN LENGTH

UTION OF CAROLINA BAYS LARGER THAN 800 FEET IN LENGTH

by the ocean. We now have fairly good proof that the ocean temporarily flooded some of the near-coastal bays in certain areas, but most bays are too perfectly preserved to ever have been subjected to the erosion of waves and shore currents.

Cooke (1933) held (theory 5) that bays are formed through the construction of crescentic keys and segmented lagoons through the force of a dominant southeast wind. The theory was based upon the occurrence of a chain-like arrangement of a few small bays aligned parallel to beach ridges and swales in the Myrtle Beach, South Carolina, area. This theory assumes that the formation of bays took place in long narrow lagoons, between sandy beach ridges under the influence of a strong southeast wind. This wind would set up elliptical currents which would scoop out elliptical depressions with the long axis parallel to the direction of the wind; bars separating the different bays would be formed across the lagoon.

Unfortunately for this theory, many bays in the Myrtle Beach area cut across both beach ridges and swales or lagoons. Some are even found entirely on high ground, and a careful inspection of the aerial photographs of the very bays chosen by Cooke to illustrate this bay origin seems to show that some of the bays in this chain cut across both lagoon and bay ridge. A study of the distribution of bays in general shows that they occur as frequently on uplands and slopes as in the lowlands. Further, there seems to be no good reason for supposing that there were dominant southeast winds in the "bay area."

The above theory of bay formation was modified by Cooke (1940) into a new theory which held that bays are formed in any confined body of water by the formation of elliptical eddies directed through gyroscopic effects of the earth's rotation, so that their elongation direction is northwest in the Northern Hemisphere. The ellipticity of the bay supposedly is a function of the sine of the angle of latitude.

The chief objection to the theory is that most of the bays do not have the correct elongation direction, many differing by as much as 30°, and no bays of this type are known to be forming at the present time.

Solution as the chief cause of bays was advocated by Douglas Johnson (1936a): "Bays are essentially the product, direct or indirect, of solution; and the encircling rims accumulations of wind drift sand." L. L. Smith (1931) had shown that many of the depressions in the Coastal Plain of South Carolina are due to solution even in areas where lime or marl are not an important factor, but did not claim that solution was responsible for bays. Some of the objections to this theory, briefly stated, are: (1) Other areas seemingly as susceptible to solution have no bays; (2) Inland bays seem as young as bays near the coast; (3) Since the bays theoretically are lengthened by solution, down slope (generally southeast), the best developed sand rims would not be expected here but rather an absence of rim.

A. K. Lobeck (1939) supported the solution theory but with slight modifications in respect to currents and wind. He also attempted to explain the formation of the magnetic spot highs to the southeast of the bays as due to the redeposition of the iron leached out of the bays.

The objection to this theory is that such deposition would take place as iron hydroxide in a long line near the surface and could not give a typical spot magnetic high area. No magnetic high of linear character running northwest-southeast from a bay is known. Lobeck's theory presupposes drainage of the bays to the southeast, which is seldom the case.

Douglas Johnson (1942) presented a new theory of bay origin, finding all previous theories, including his own, inadequate. He combined several processes of terrestrial nature into the artesian-solution-lacustrine-aeolian hypothesis. It differs from his former theories by the addition of the activity of artesian springs in association with the work of ground water. This theory, to be discussed later, does not explain any more than do other terrestrial theories the limited distribution of bays and many known facts.

Another theory which assigns the bay origin to "blow outs" by wind action has been suggested by a number of scientists in their early consideration of bay origin. I do not know of anyone who has studied the bays in the field who upholds this theory at the present time.

After study of rounded lakes and lagoons in the Coastal Plain area of Massachusetts, Raisz (1934) concluded that there is a tendency for

lakes in unconsolidated sands to become elongated in the direction of maximum wind velocities. It has been thought probable that the strongest winds would blow from the direction of the great ice mass during glacial time. This theory is not unlike early theories of both Johnson and Cooke, largely abandoned by both as prime factors in the formation of the Carolina Bays. Glacial winds should have had little force as far south as South Carolina and Georgia where bays are numerous and should have had much force in the northern Coastal Plain areas where bays are very scarce or entirely absent.

The most recent hypothesis of terrestrial origin was proposed by Chapman Grant (1945). It holds that the activities of shoals of fish are responsible for the formation of the shallow sand-rimmed depressions which we call bays. Such activities supposedly are located where artesian springs of fresh water appear in near-shore marine areas. The many cogent objections to this proposal are discussed later.

Meteoritic Theories of Origin

According to Melton and Schriever (1933), bays were formed by the infall of meteorites of a probable comet mass travelling in a general southeast direction and hitting the earth at a small angle to the horizontal. The theory has many good points and others that require modification. The authors assumed that the ringed depressions were caused by the splash effects of the meteorite hitting the earth with vertical incidence of about 55°. On account of the partially destroyed appearance of many bays along the coast, Melton held that the bays were older than the latest Pleistocene terrace. A nearly uniform direction of long axis orientation was assumed for the area of their occurrence.

One of the chief objections raised to the theory is that, for such large depressions, the meteorite must have had great mass and velocity and when such mass hit the earth the effects would have been more like that of an explosion, thus producing a circular rim. No fused glass or fragments of meteorites have been found associated with the bays. Various points will be discussed later.

The revised meteoritic theory accepts the meteoritic shower but assumed that the elliptical, shallow, sand-rimmed drepessions were formed by the action of the air-shock waves associated with the falling meteorites. The meteorite forming each of the bays, which might be in one mass or in several masses, would fall in the central portion of the bay and would cause a relatively small area of disturbance. The revised theory was suggested by Prouty (1934a: 1935) and further developed by his associate MacCarthy (1935). According to the author's view, this revised meteoritic theory answers the known facts about bays. For significant new evidence, see later, under Contour and Filling Material of Carolina Bays.

More Important Facts Concerning Carolina Bays

Following are the more obvious facts concerning the Carolina Bays:

1. Bays are geographically restricted to the coastal plain area between southern New Jersey and northeastern Florida, with most of the bays in the two Carolinas and northeastern Georgia.

2. Bays are very irregular in their distribution and size.

3. Bays have no relationship to geological formations, geological age (older or younger terraces), or topography. Some bays are on interstream flatlands, others on valley slopes, or older stream terraces, and a few on the older portion of the present flood plain of streams.

4. Toward the northeast and southwest extremities of their occurrence, the bay groups are less numerous and smaller, but as variable in their distribution and size as they are nearer the center of the area.

5. No bays have been found outside of the sand-covered coastal plain or its erosional remnants, and none should be expected there according to the air-shock wave meteoritic theory. Large rimmed depressions would not have been formed as readily in the clay soil of the Piedmont as in the sandy Coastal Plain, and such rimmed depressions in clay soil would be more readily destroyed by both erosion and sedimentation. On the other hand, buried meteorites would be better preserved in the clay soil than in the pervious, sandy soil. The area to the northwest of the known bay country

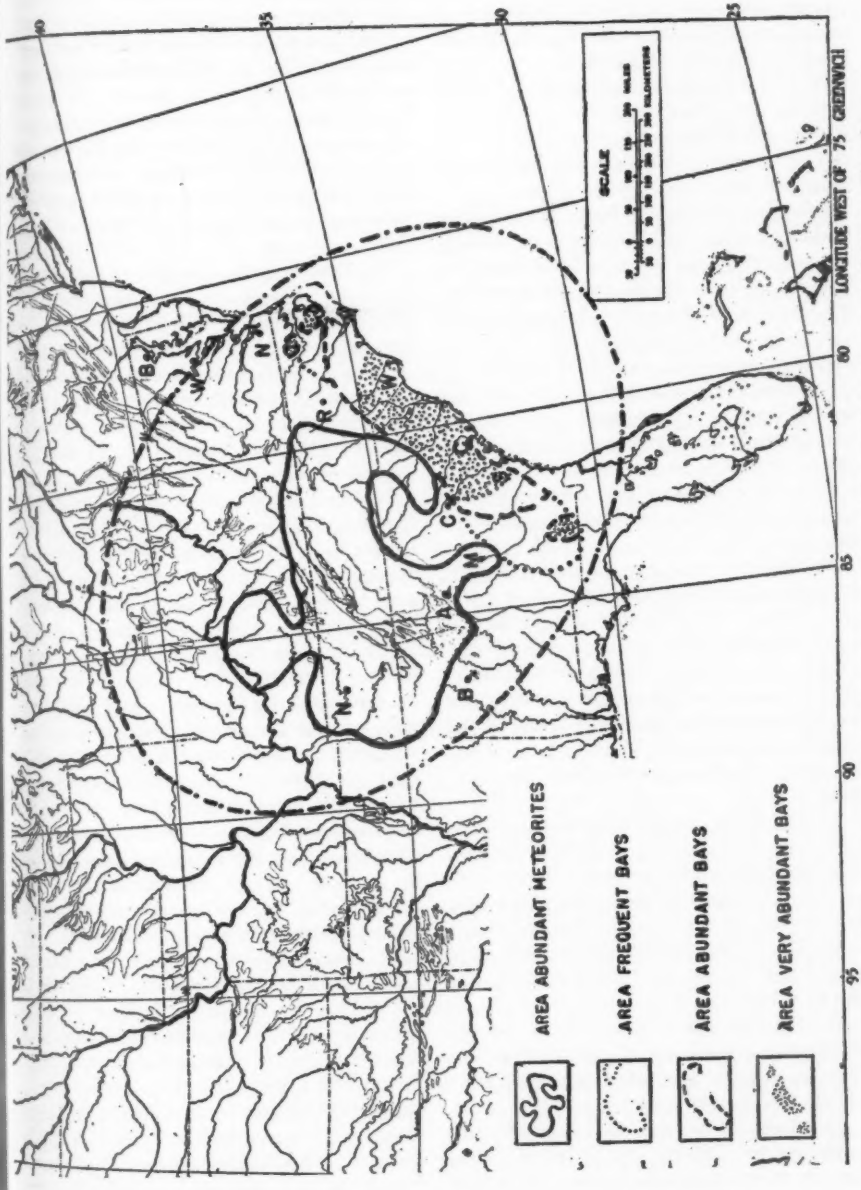


FIGURE 1.—MAP SHOWING GEOGRAPHICAL RELATION OF AREA OF ABUNDANT METEORITES TO CAROLINA BAY AREA

has yielded more meteorites than any other equal area in the United States (Fig. 1).

6. An estimate of the probable number of bays, large and small, in the Atlantic Coastal Plain area is about half a million.

7. The direction of elongation of the bays is controlled, seemingly, by a force which varies slightly and more or less regularly between the two extremities (northeast-southwest) of the occurrence area.

8. An area of unusually large bays and elliptical lake basins, which includes parts of Cumberland and Bladen counties, North Carolina, is elongated in a direction about parallel to the direction of elongation of the individual bays (Pl. 1). This pattern is repeated elsewhere.

9. Bays have sand rims which stand above the general level of the land and are best developed generally at the southeast end of the bay, especially the eastern portion of the southeastern end. The poorest development, as a rule, is along the west and northwest sides, although even there some bays have fairly well developed rims.

10. Rimmed depressions of similar ellipticity can readily be formed by the air-shock waves created by a rifle bullet shot at an angle into a light powder, such as plaster of paris powder, resting on plastic clay. The rimmed shock-wave depression made in the powder is many times the diameter of the hole made in the plastic clay by the projectile. The ellipticity of the depression depends upon the angle of penetration.

11. The larger bays generally have larger rims, but local conditions modify the size. Rims are better developed where a bay is located in a high and dry sandy area rather than in a low and wet sandy area (Pl. 4, fig. 1).

12. The deepest part of the bay is usually toward the southeast end and a little west of the axial line (Fig. 12).

13. The similarity of development and the condition of preservation of bays in all parts of the "bay country" seems to indicate that they are all of about the same age.

14. Similarity of rock character, climatic conditions, groundwater, and topography seem to be as favorable for the formation of bays in bordering areas as in the areas of known occurrence.

15. Elliptical sand-rimmed bays are not being formed anywhere in the world at the present time as far as known.

16. There are no well developed bays or beach ridges for a distance of 7 miles northwest from Myrtle Beach, South Carolina. This area was either covered by the ocean at the time of the formation of the bays, or else the ocean returned to cover and destroy the bays formed in the area. In many low, near-coast areas, the bays have apparently been considerably effaced by marine or lagoonal sedimentation and erosion.

17. Most bays are associated with other bays of slightly different age. These associated bays frequently overlap. The overlapping younger bay completely obliterates that portion of the older bay overlapped. Occasionally a small bay is contained wholly within the area of the larger bay. The rim of the smaller bay usually rises above the level of the swamp or lake of the larger bay. Some unusually elongated or unusually broad bays are found to have been formed by a number of associated and overlapping bays. The overlap direction of twin or multiple bays in North Carolina is generally more to the northwest than to the west, thus creating some unusually elongated multiple bays in that area (Pl. 8). Toward the southwest, in the South Carolina—Georgia area, such overlap direction is frequently more toward the west, so that the multiple bays in that area are broadened rather than lengthened (Pl. 7, fig. 1; Pl. 13; Pl. 15). Some oval or heart-shaped bays appear to derive their shape from two or more overlapping bays which have a slight convergence of their long axial directions toward the southeast; in such cases, the bay unit on the west has the smaller azimuth (counterclockwise rotation) of orientation (Pl. 15).

18. Many bays have more than one rim, usually along the southeast and east sides (Pl. 6; Pl. 7, fig. 2; Pls. 9, 10). In some cases where rims are broad and high, these successive rims are the result of multiple bay formation. In these bays, each newer overlapping bay is formed slightly more to the west (Pl. 7, fig. 1) or, in other cases, to the northwest or north of its predecessor (Pl. 6, fig. 2). In many cases of overlap, the only portion of the older bay not concealed by the overlap is a small crescentic portion of one side. Where the inner rims are comparatively small and appear more or less

symmetrically placed in respect to the plane of symmetry of the bay and with development limited to the southeastern two thirds of the bay, the origin of the rims may be associated with the forces forming the larger and outer rims.

19. In a number of cases, a later-formed bay has cut across earlier-formed outer and inner rims of a single bay (Pl. 14, fig. 2), thus indicating that the two types of rims were closely associated in time of formation, if the meteoritic theory of origin is assumed.

20. In soluble rock areas, many of the bays are being modified by solution and some can now be classified as sinks—"bay sinks," Sand rims are being lowered in some regions by groundwater moving from the bay underneath the rim to a stream which is "heading up" toward the bay and at a lower level than the water table in the bay.

21. A very small proportion of bays drained by streams are drained from the southeast end, but more often from the southwest, west, northwest, or east sides, indicating drainage by normal headward erosion of tributary streams. (Pl. 1; Pl. 6, fig. 1).

22. Many bays have been partially filled by stream deltas, more often entering from the northwest, north, or northeast sides. (Pl. 10)

23. Many bays have been partially filled by windblown sand from the southwest, west, and northwest. In such cases the sand is usually finer-textured than that of the average rim (Pl. 12).

24. Sand dune areas in many cases extend northeastwardly from the east and northeast sides of the bay (Pl. 9).

25. Samples taken from one medium-sized bay just beneath the thick peat deposits show a gradation from medium-coarse sand near the sides of the bay to silt in the central portion of the bay.

26. Near Myrtle Beach, South Carolina, the inland waterway cuts through the north-central portion of two small contiguous bays to a depth of about 25 feet. The two continuous shell beds found elsewhere along the canal are absent in the central portion of the section through each of these two bays (Fig. 24). These shell beds must have been removed by either chemical or physical means. Nowhere else along the canal beneath the peat deposits, former swamp areas but not bays, have the shell beds been removed.

27. In Bladen and bordering counties, North Carolina, where large bays and bay lakes are numerous, it is not unusual to find large areas with more than 50 per cent of the surface covered by bays, and in much of this area the bays will also have an overlap of 10–25 per cent or more (Fig. 3).

28. Practically every bay, large or small, surveyed by magnetometer has a well defined spot magnetic high or highs associated with it. If there is a single spot high, it usually occupies a position a little east of south from the southeast end of the bay at a distance about that of the short axis of the rim from the southeast end (the "Prouty Rule," so-called by Douglas Johnson, 1942). If there are two or more associated spot magnetic highs, the distance of each from the southeast end of the bay is considerably less than in the case of a single spot high. There is considerable variation in the direction of the spot highs from the bays as well as in the size of the spot highs in relation to the size of the associated bay. This variation seems logical from the variable conditions encountered.

29. In some parts of the coastal plain area, linear magnetic highs are present. These usually trend in a northeast-southwest direction and tend to swell and diminish along the strike, making it difficult to entirely eliminate their effects from the spot high magnetic readings.

30. Many of the bays have a slightly flattened elliptical border on the southwest side. In some cases this may be accounted for by eastward- or northeastward-drifting sand; in other cases, the reason is not clear but may have some connection with the development of the deeper part of the bay, which is toward the southeast end and to the west of the median line. Also, in multiple bays, the later-formed bay usually is responsible for the northwest portion of the bay rim and this later formed unit of the multiple bay has a slight counter clockwise orientation from that of the earlier formed unit of the bay responsible for the southern portion of the west rim. These conditions result in a somewhat flattened southwest rim.

31. The rim sand of bays is, in general, a little coarser than the average sand of the

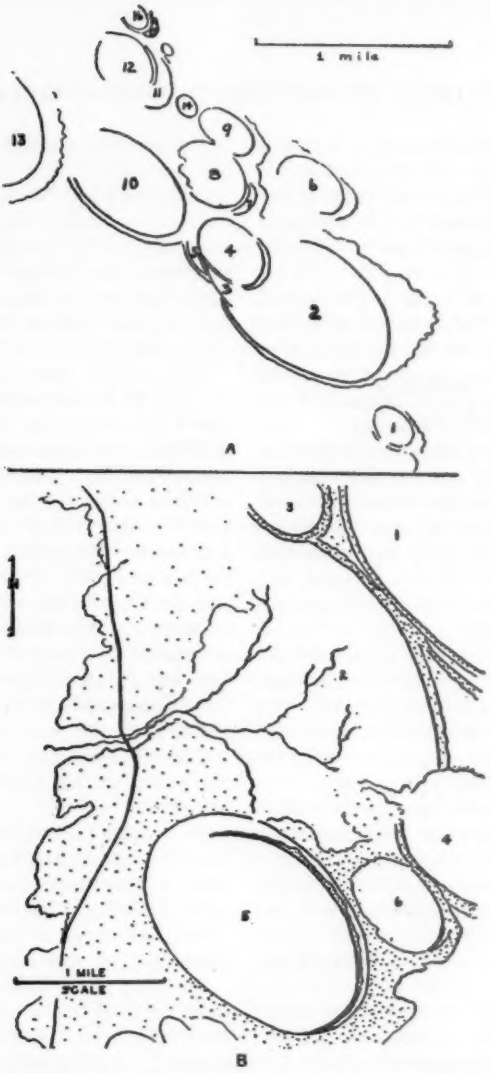


FIGURE 2.—BAYS IN BLADEN AND CUMBERLAND COUNTIES, NORTH CAROLINA

A. Nineteen bays are recognized here, 18 in a strip about a mile wide, extending northwest-southeast through picture. Much of area is swamp. The visible bays occur on ground which rises slightly above the general level. Doutless other bays occur in the lower and more swampy area, especially in the south portion. Bay Number 2 is about 1 mile long. Several groups of bays overlap. The most conspicuous overlapping group contains bays 5, 2, 3, and 4, named in order of formation. Three other groups have two overlapping bays each: 7–8, 11–12, 15–16; in each group, the northwest bay is the overlapping or younger bay. This is the general rule of overlap, although there are many exceptions. Note better development of bay sand rims along east side of southeast ends of bays. Development of rim also depends on its position in respect to sandy or swampy land. Southwest rim of bay 2 is less well developed than that of bay 10 because it was formed in lower and more swampy ground; southeast rim of bay 4 is fairly well developed because it was formed in the shallow part of bay 2. Drainage from bay 2 is through the southwest rim.

B. Two well-formed bays, nos. 5 and 6, were formed in sandy area considerably above the level of the swampy ground shown in the southwestern part of the picture. Drainage from both bays is northward. Both have nearly perfect main rims and a single thin inner rim. In the larger bay, the inner rim seems to belong to a younger and smaller bay, whose center is slightly west of the center of the bay it overlaps. The southeast end of a very large "ghost bay", no. 2, has been obliterated by the later formation of bays 5 and 6 and the small "ghost bay", no. 4. North and west portion of the large "ghost bay" has been concealed by drift sand, moved apparently largely by flood-water action in the comparatively lower ground. Bays are numbered from oldest to youngest.

It is difficult to explain the origin of these bays with their peculiar overlap and northward and westward drainage by any theory other than the meteoritic theory.

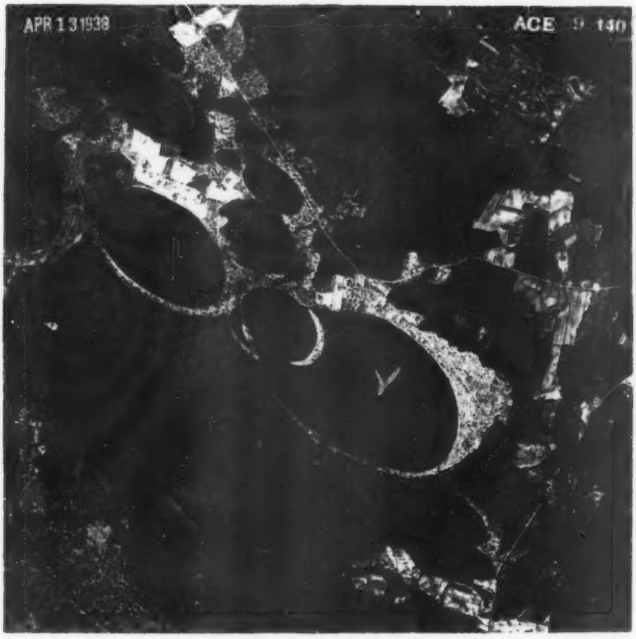


FIGURE 1. BAYS IN BLADEN COUNTY
See Figure 2A for descriptive data.

FIGURE 2. BAYS IN CUMBERLAND COUNTY
See Figure 2B for description of bays.

BAYS IN BLADEN AND CUMBERLAND COUNTIES, NORTH CAROLINA

FIGURE 1. SMALL BAYS NOW IN CULTIVATION
Some project across waterways or are partly concealed by river swamps.

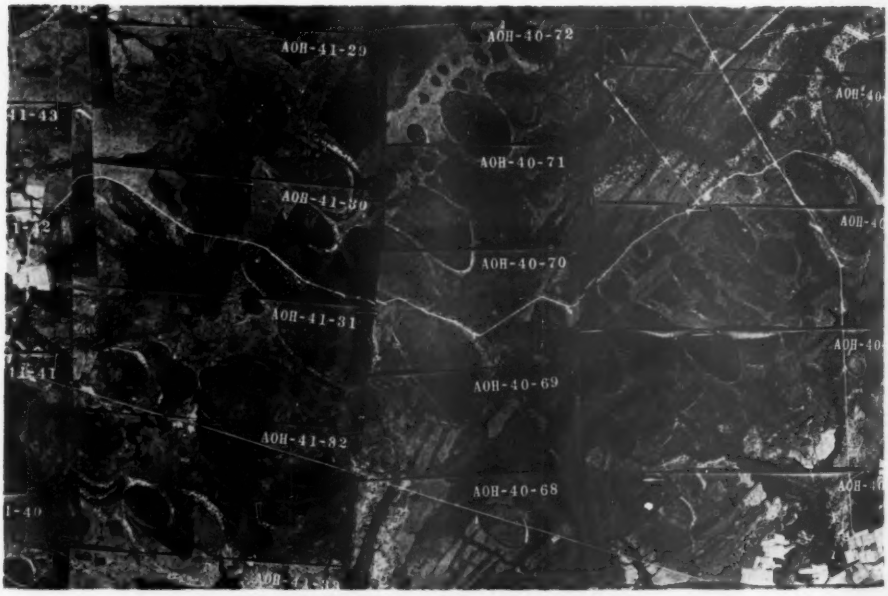


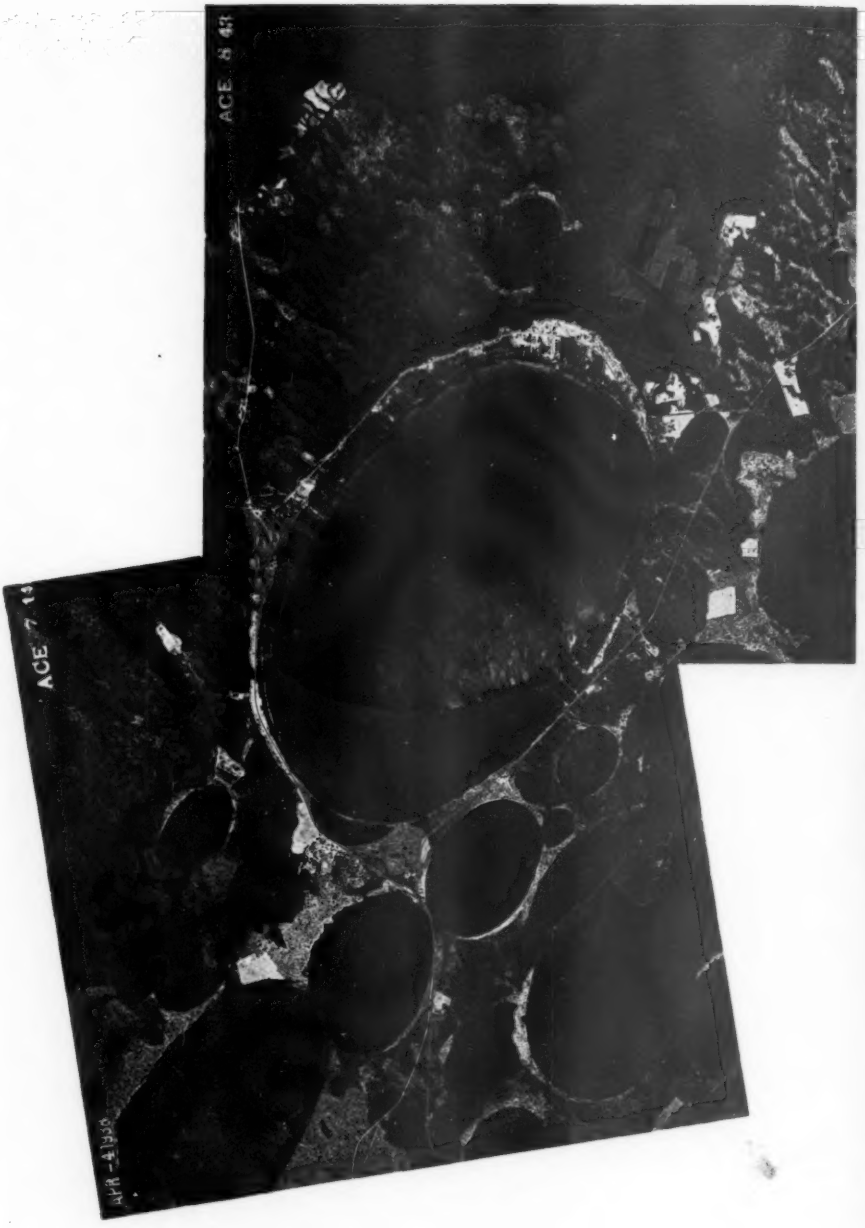
FIGURE 2. BAYS CUTTING BEACH RIDGES AND SWALES
Most of the larger bays are multiple bays. Note two unusual double bays in southwest corner.
Area about 4 miles from the coast.

BAYS IN SCOTLAND AND BRUNSWICK COUNTIES, NORTH CAROLINA

FIGURE 1

FIGURE 2

BAYS IN BLADEN COUNTY, NORTH CAROLINA



WHITE LAKE BAY, BLADEN COUNTY, NORTH CAROLINA

area. This is to be expected according to almost any theory, including the metoritic air-shock wave theory. The coarseness is emphasized by the down wash of the finer material or by the very important action of ants which live on the dry sand rims. In building their nests, the fine grains are left below and the coarse ones are brought to the surface; also wind tends to move the fine sand grains from the rim. If air-shock waves are responsible for the rim formation, one would expect the fine sand particles to be carried farther from the depression than the coarse particles.

32. The sand in the rim shows little, if any, stratification. The formations beneath the rim appear to be undisturbed. There are no known deep sections across the bays at the critical points (deepest area in bay). A rumor of the presence of a "pipe" of disturbed ground beneath bays (McCampbell, 1943) has not so far been verified.

33. Metallic iron,[2] fragments of basement rock, or fused glass have not been found in association with any of the Carolina Bays. They should not be expected in view of the porous soil and climatic conditions.

34. All bays were formed on the superficially sandy Pleistocene terraces of the coastal plain and are younger than any of the well developed beach ridges with which they are associated, as shown by the fact that they cut across these ridges. An exception to this is found in some bays near the coast, where temporary marine flooding has both largely destroyed the sand rims and built faint beach ridges and swales across the bays (Fig. 19).

35. In a few places there is direct evidence that the sea has encroached upon some of these bays since their formation and has again with-

[2] The recently discovered deeply oxidized Sardis Meteorite may be an exception.

PLATE 4.—BAYS IN BLADEN COUNTY, NORTH CAROLINA

FIGURE 1.—OLD DRAINAGE AREA OF CAPE FEAR RIVER

Bays numbered 1, 2, 3, 4, 5 occur within this area

FIGURE 2.—SALTERS LAKE

Showing greater retreat of bay lake toward deeper southeast end than does White Lake. Small bay at northwest end of Salters Lake is older than the big bay. Assuming meteoritic theory of origin, hot compressed air-shock waves accompanying the fall of the meteorite blew violently outward from the point of contact of the cone of compressed air. This action broke through southeast rim of little bay and blew sand violently toward northwest in small bay area. Normal rim development was here carried farther northwest especially in central portion of little bay opening, where resistance was less. After formation of reverse rim in south-central part of small bay, shock wave reformed and broke against shallowing shore at northwest end of little bay. If this sand bar near entrance into little bay had been formed by eddy or shore-current action, bar would have more directly connected the two points of entrance of small bay.

Note that long axis of remnant lake in Salters Lake Bay has greater azimuth (is turned more clockwise) than axis of the bay. Most bay lakes which do not now occupy full area of bay show same phenomenon. Good examples are Jones Lake and White Lake, in Bladen County. This turning of axial direction reflects contour of lake bottom and is possibly explained by meteoritic theory. As meteorite penetrated the earth, it was deflected more and more to west, owing to earth rotation, thus making tubular opening maintained by escaping gas also turn more in clockwise direction. All shrinking bay lakes seem to follow same change pattern.

PLATE 5.—WHITE LAKE BAY, BLADEN COUNTY, NORTH CAROLINA

Unlike many of the larger bays, it has no inner rims. Magnetic spot high from this bay is also a single spot high. All bays shown here except possibly one are single bays.

White Lake is one of several bay lakes in Bladen County. It is one of the few lakes known to now have lake-bottom springs. These springs are most abundant toward the deeper (about 15 feet) southeast end of the lake. Lake is withdrawing from northwest as water table is lowered. Lake and swamp at northwest drain westward. Lake has been gradually shrinking toward its deeper southeast to south end. A smaller bay existed at northwest end of White Lake Bay before formation of the big bay which obliterated overlapped portion of small bay. Rim of larger bay formed across entrance to small bay has here a shorter radius of curvature than elsewhere. *See* Salters Lake Bay (Pl. 4, fig. 2).

Much of the area south and east of White Lake is relatively low and has been considerably flooded, eroded, and the bays partially obliterated.

drawn, as in Blythe Bay, Wilmington, North Carolina, where peat deposits in the bay have been covered by sediments of probable marine origin. Later elevation and stream erosion has cut through the sediments and into the peat.

36. A few are known to have lake bottom springs. Most of these springs are near the southeast end of the bay.

37. Bays are generally largely filled with peat which apparently has a maximum thickness of from 15 to 30 feet. The peat filling reaches an elevation a little below the general level of the surrounding area. This elevation is governed by the height of the water table.

38. Bottom samples from the deeper part of some of the bays in Bladen County, North Carolina, taken from beneath the peat deposits, show a thickness of several feet of light-colored silt which, according to B. W. Wells (personal comunication) is of wind blown character. The deposition of silt over the coarse bottom sand shows that the bays were formed suddenly and were soon filled with water, then followed sedimentation from a wind swept barren area. It is apparent that a slow sinking depression such as postulated by either solution or artesian springs could not yield the type of profile shown in these bays. According to Wells, the slow sinking postulated by either the solution or the artesian spring theory would yield deposits containing shallow-water or marsh-plant pollen. Instead of this there is a silt deposit without marsh-plant pollen made in deep water. The silt grades at top into aquatic peat containing pollen from water lillies and from trees of boreal or cold climate type.

Distribution, Coverage, Number, and Grouping of Carolina Bays

The Carolina Bays are entirely confined in their occurrence to the Atlantic Coastal Plain and a few coastal plain outliers (Pl. 1). The large percentage of these rimmed, elliptical depressions are found in South Carolina and southeastern North Carolina. The bays also occur in rather large numbers for some distance to the west of the Savannah River in Georgia. Scattered bays also occur in the south and north central parts of the Georgia Coastal Plain in groups and clusters, as they do in the north central part of the Coastal Plain of North Carolina. A very few scattered bays are to be found even in extreme northeastern Florida and in the Chesapeake Bay Region of Virginia and Maryland, and three or four questionable bays exist in New Jersey.

Concentration of large bays occurs in some localities as does the concentration of small bays in other localities, but in general there is a fairly uniform mingling of sizes in the distribution. In some parts of the bay area, a number of overlapping bays occur in a northwest-southeast line, giving elongated "multiple bays." In other parts of the area, several bays overlap, making broad, more or less pear-shaped or heart-shaped "multiple bays." Roughly speaking, the large bays occur in greater proportion in two large districts, one in the southeastern North Carolina-northeastern South Carolina district and the other in the southwestern South Carolina-northeastern Georgia district. The North Carolina district includes the large Lake Waccamaw bay which has a length of over 6 miles, a sand rim at the southeast end about 23 feet above the lake level, and a width of over 2000 feet. At several localities in the Carolinas, small bays are found within a few hundred yards of the inner edge of the coastal plain. In a few localities in Georgia, "ghost" or remnant bays are found on coastal plain outliers a little distance into the Piedmont from the unbroken coastal plain line. These outliers were formerly part of the Coastal Plain before streams removed much of the sand cover from the underlying Piedmont rocks.

Some bays were without doubt formed in the lowlands, in many cases river bottoms, as well as in the interstream areas and valley slopes. Skeleton bays can be seen in a few places in the floodplain of the Cape Fear River and partially destroyed bays can be seen along the present river banks (Pl. 4, fig. 1). Some bays project across waterways or are partly concealed by river swamps (Pl. 3, fig. 1). There are no bays to be seen in the more recently formed portions of the Coastal Plain and for 7 miles inland from the coast town of Myrtle Beach, South Carolina. Going inland and north toward Conway, South Carolina, the first bays to be seen show signs of having been partially destroyed by wave action (Fig. 19). It is logical

to conclude that the bays were either formed in shallow water along the sea coast of that time and were partially destroyed before the ocean retreated to its present position, or that the ocean raised after the formation of the bays and migrated back to the position of the partially destroyed bays before retreating to its present position. Partial destruction of bay rims is to be seen in a number of places along the coastal areas and in places several miles back from the present shore. Study of plant remains in the sediments of the present coastal swamps and beach ridges by Professor Wells (personal communication) confirms the theory that there has been a relatively recent sea advance and retreat along a considerable portion of the coast line of the Carolinas. In the Wilmington, North Carolina, area, as pointed out also by Wells (1943), peat deposits in Blythe Bay which have been covered by several feet of marine sediments are now exposed by stream erosion. This seems to show a marine invasion and retreat some time after the formation of the peat in the bay.

As far as known the Carolina Bays were formed under both geographical and time limitations, later than the formation of most of the Pamlico Terrace.

The area of distribution of the bays is about 83,000 square miles. Of this area, perhaps 43,000 square miles have very few or no bays. The bays cover, including overlap, roughly about 10 per cent of the surface. Where bays are large and thickly distributed, they may cover more than 50 per cent of the surface. Two large areas in Bladen County, North Carolina, were measured. In one of these, 7 miles long by 4 miles wide (Fig. 3), the area covered by bays was found to be a little over 50 per cent. Another section of Bladen County, 5 miles by 4 miles, had a bay area of 67½ per cent. In places, 20 bays to the square mile, each longer than 500 feet, have been counted. Some of the large bays cover several square miles. These, in some cases, may be made up of several overlapping bays. Many bays are concealed in heavily wooded, swampy, or river-bottom lands.

A conservative estimate of 3.5 bays to the square mile, each longer than 500 feet, gives an estimate of 140,000 bays of moderate and large size. It is almost impossible to estimate the number of small bays. One might be justified in roughly guessing that the total number of bays, large and small, is about half a million.

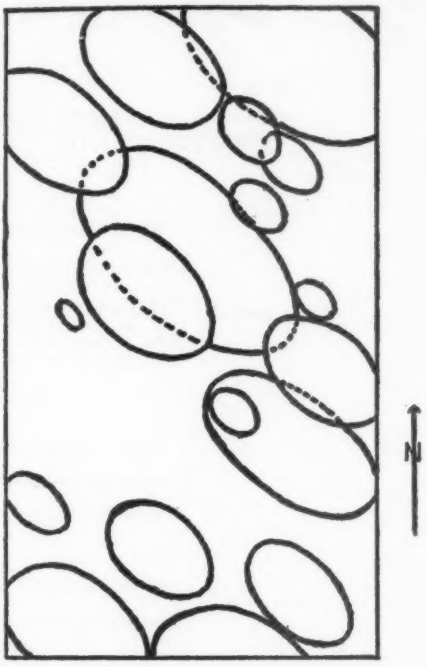


FIGURE 3.—CONCENTRATIONS OF BAYS IN PORTION OF BLADEN COUNTY, NORTH CAROLINA

Overlay of aerial photography of area 7¼ miles northwest of Elizabethtown. About 64.5% of area covered by bays, including overlap. Smallest bay shown is 1900 feet long. If the large number of small bays not shown were considered, the area of overlap would be considerably increased.

CHARACTER OF BAY RIMS

If we assume that the northwest end of the bays represents the 12 o'clock position, in general bay rims are best developed between the 4 o'clock and the 6:30 o'clock positions. The inner slope of the rim is usually a little steeper in that portion of the rim lying between the 7 and 11 o'clock positions. Where two bays join, for example Junkyard Bay and Guys Bay, Manning Quadrangle, South Carolina, the bay

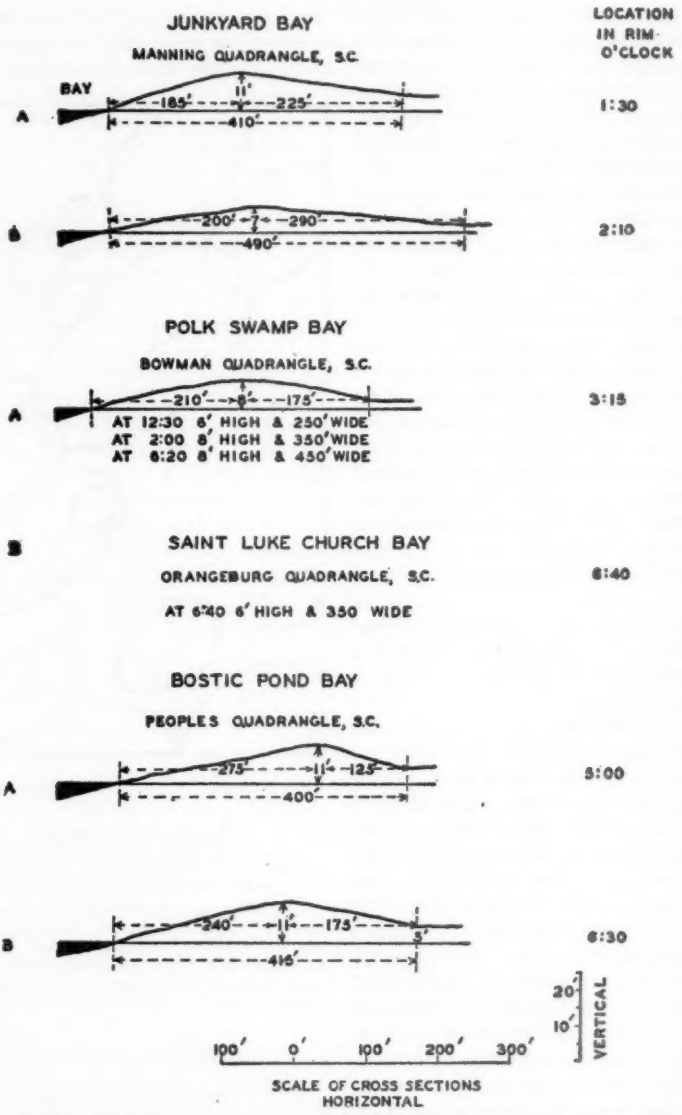


FIGURE 4.—PROFILE SECTIONS SHOWING THE NATURE OF SEVERAL BAY RIMS, SOUTH CAROLINA

rim at the point of junction has a greater height than at any point. In general the high point of the cross section of the rim is nearer the outside of the rim. In only a few cases do rims have nearly flat tops.

Any generalization concerning the cross-section characteristics of bay rims is not satisfactory because of various types of modification under different environments by wind, water, and the original character of the ground in which the bay has been formed.

A number of cross-sections taken through

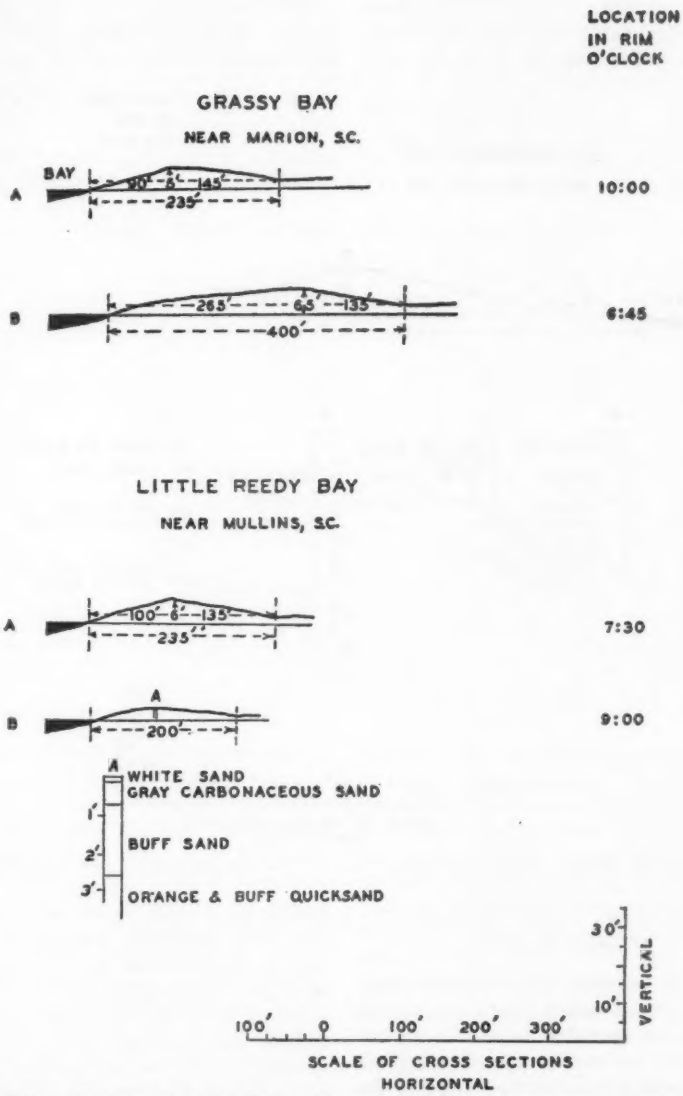


FIGURE 5.—PROFILE SECTIONS THROUGH RIMS OF GRASSY BAY AND LITTLE REEDY BAY, SOUTH CAROLINA

various portions of the bay rims of several different bays are given (Figs. 4, 5, 6, 9).

Table 1 gives the height and width of 14 bay rims well distributed through North Carolina and South Carolina. The height is the number of feet the bay rim rises above the swamp or lake level in the bay, and the width is the distance in feet from the inner to the outer edge of the rim measured at right angles to the trend of the rim at that point. The numbers 1 to 12 along the top of the table refer to the position of the respective observa-

tion on the rim. The rim is numbered like a clock with 12 o'clock at the northwest end and 6 o'clock at the southeast end.

Melton and Schriever (1933) discussed chiefly the bays near the coast and those in the Myrtle Beach area in particular, to which area the then

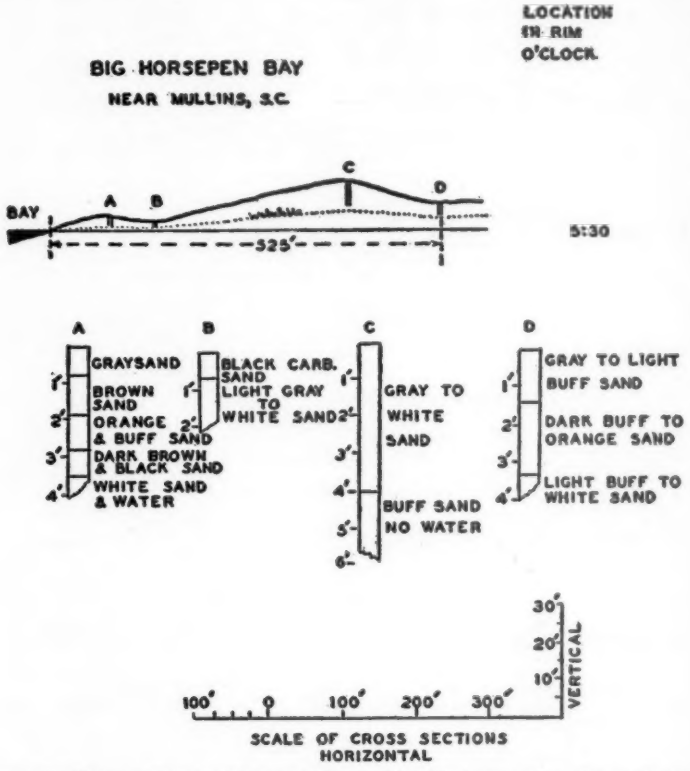


FIGURE 6.—PROFILE SECTION THROUGH RIM OF BIG HORSEPEN BAY, SOUTH CAROLINA

CONTOUR AND FILLING MATERIAL OF CAROLINA BAYS

L. C. Glenn (1895) examined some small elliptical bays and made a general cross section of one of them. According to him, this bay had been drained and was being used for agricultural purposes. The surface was composed of a dark, fertile, compact clay. The dark color was undoubtedly derived from charcoal left from the peat fires common in the dry seasons. The clay according to Glenn:

> "... extends down some fifteen to twenty-five feet as is proven by driven wells that have been forced down through it. No water is gotten until the pipe reaches the underlying sand when the water rises to general water level, within six or eight feet of the surface."

existing aerial photographs were largely confined. They refer to the filling material of these bays as peat underlain by carbonaceous soil. In some of the smaller bays, the filling was estimated to be 25 feet or more thick. These authors were impressed with the "blurred" condition of many of the bays near the coast and considered that these had been covered by sea water at one time. Such bays were silted largely by marine action: "This aggradation, also, may have been accomplished in part by subaerial forces operating on the Coastal Plain prior to the invasion." The marine type of filling referred to by Melton and Schriever would necessarily have to be in the low and near-coast part of the Coastal Plain.

Douglas Johnson (1942) says:

"Well records and borings with soil auger have led different observers to conclude that in bays of average size the craterlike depressions may have total depths below the general plain level of from fifteen to fifty feet, the filling consisting of dark clayey, carbonaceous sand or silt, sandy or clayey loam and peat."[2]

The only detailed exploration of bay filling so far has been by M. F. Buell (1939; 1946a; 1946b). His explorations were concentrated on Jerome Bay which is about 6000 feet long and is located on the border of Bladen and Cumberland counties, North Carolina. Samples were taken along both the long and the short axes of the bay and down to the sandy floor of the depression. The deepest part of the bay is southeast of the short axis and southwest of the long axis, (a point a little south of the center), about 59/100 the length of the bay from the northwest end and 54/100 the width of the bay from the northeast side. This means that the cross-section did not reach the deepest part of the bay which is probably a foot or so deeper than shown on the cross-section (Fig. 9). Toward the northwest from the deep point, the bay floor rises rather rapidly to a comparatively shallow platform consisting of two gently sloping terraces. Toward the southeast from the deep point, the bay rises to a low platform made up of two gently sloping terraces, the upper part of which changes to a rapidly rising slope as the south rim is approached. The cross-section along the short axis shows a more rapid rise of the floor toward the southwest than toward the northeast, while both slopes show double terracing similar to those of the long cross-section.

A careful study of a number of the bays in Bladen County verifies the fact that Jerome Bay has a typical basin contour. The lakes in the bays studied are all being gradually reduced in size by the lowering of the water table through deeper stream erosion of the area. In all of these bays, the retreat of the diminishing lake is towards a point south of the center of the bay—the deepest point in the bay.

The contour of the bay floor, as stated above, does not fit either the solution theory or the artesian theory of bay origin, both of which preclude terraced slopes and steeper gradients on the southeast and southwest sides. The contour of the bay depression does, however, fit the conditions postulated in the air-shock wave meteoritic theory. The deep point nearer the southeast end of the bay points to an angular infall from the northwest, and its position to the west of the long axis points to the deflective force of the earth's rotation during the penetration. The deeper digging out of the depression toward the southeast would be the result of the greater force of the shock waves here and also because it is the area of penetration of the meteorite. The terraces could be

TABLE 1.—HEIGHT AND WIDTH OF SOME CAROLINA BAY RIMS

NAME OF BAY	HEIGHT OF RIM IN FEET AT CLOCK POSITION												WIDTH OF RIM IN FEET AT CLOCK POSITION											
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
WHITE POND	8				9		8						275			380		400						
JUNKYARD		4.5				7								200			1200							
WARDBOO SWAMP	0				6								0				750							
POLK SWAMP		8		8			7.5					6		350		350			450					250
ROWESVILLE SWAMP	8												400											
ST LUKE'S CHURCH BAY					4.5		6										250		350					
SWALLOW SAVANNA			5*		10.5 8 10				7						400			370	800					
LEVY BAY						7.5												550 700						
LOWER BAY MULLINS					4*	5										380	600							
MIDDLE BAY MULLINS							5												580					
LITTLE SISTER BAY				4.5												350								
LITTLE REEDY BAY							5		3*								200				165			
GRASSY BAY						7*			3*	5" 5									390		150	225 230		
WACCAMAW LAKE					23*												2000*							

explained by pulsation in the air-shock waves or by gas explosions associated with the penetrating meteorite.

The cross-section of Jerome Bay taken from Buell's report shows the filling of this bay from the top down as follows:

"A continuous, thick, coarse and tough mat of tree roots and the roots and rhizomes of shrubs.

"*Black peat*, very fine, soft and sticky when wet and dries to a hard, brittle mass. It consists of small bits of charred plant fragments and quantities of fine charcoal. Pollen is fairly abundant in lower portion.

"*Brown peat* with varying amounts of partly decomposed macro fragments and here and there an abundance of logs. Pollen is abundant and well preserved.

"*White clay* mixed near the bottom with coarse sand, and toward the top with bits of wood and plant fragments."

The sand underlying the peat and clay deposits seem to show a tendency to become finer toward the deeper part of the basin and away from the rim. (Samples submitted to the author by Mr. Buell).

The peat deposits described above follow the general rule in regard to peat deposits which are frequently burned over. These are above the water table and are subject to fires in the dry season and have admixed charcoal in the upper part, while the brown lower part of the peat deposit has little or no admixture of charcoal.

Interest in the sediments of the bays, outside of age determination from the pollen, lies chiefly in the so-called white clay at the bottom. It would appear that this bottom and probably earliest filling, which according to Wells (personal communication) is more of a silt than a clay, was formed largely during a relatively cool period when vegetation was scanty and wind for erosion and transportation was at a maximum. Also if we assume the air-shock wave meteoritic theory to be true, all vegetation in the area would have been destroyed by the formation of the bays, thus giving the wind added power to transport dust and carry it over the lake basins which would naturally be formed in all depressions below the level of the water table. This material would tend to settle in the deeper and more quiet portion of the lake, and some of it would work down into the underlying sand. To this wind-blown silt would be added the finer particles brought into the lake by running water, and finally some of the ash from the burning peat beds. It would be impossible to explain the presence of thick deposit of silt in the bottom of the bay if the bay originated according to the artesian theory and

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PLATE 6.—MULTIPLE BAYS IN SAMPSON AND BLADEN COUNTIES, NORTH CAROLINA

FIGURE 1.—BAYS IN SAMPSON COUNTY, NORTH CAROLINA

Showing one conspicuous multiple bay about 1¼ miles long in northwest part of picture. Small bay just touching southeast end of big bay extends about a third of a mile southeast from that point, made conspicuous by clearing of vegetation from its southeast rim. Careful inspection of photograph reveals traces of 10 other probable bays, largely destroyed by action of moving water. Big bay has two rims, one considerably larger than other. Most logical explanation is that outer rim was formed first, and inner rim was formed by slightly later infall of smaller meteorite which fell a little more to the northwest than first one, which is general rule in North Carolina. Flooding which seemingly largely destroyed most of smaller bays of area has also destroyed much of two main rims of big multiple bay, especially that part in lower ground to southeast. Apparently much of sand from rims has become filling for bay, now drained northwestward by stream. It would be interesting to ascertain if peat occurs beneath this sand filling, as it does in a number of bays in neighborhood of Wilmington, North Carolina.

FIGURE 2.—BAYS IN BLADEN COUNTY, NORTH CAROLINA

Four bays ranging from about a third of a mile to a little over a mile long. Three smallest bays have no secondary rims. All four seem to have been formed on relatively higher ground where moving water has not been able to destroy bay rims, as it has apparently for "ghost bays" in lower ground. Large "ghost bay" in north-central part is hardly recognizable. Its presence is suggested by curved outline of east side, where it was formed in slightly higher ground, and by general uniformity of coloring of main portion of bay, characteristic of more uniform swamp area.

Large conspicuous bay at northwest shows four large rims and one smaller rim. Four large rims suggest infall of four meteorites of about same size; each younger one hit a little more to north and west of its predecessor.

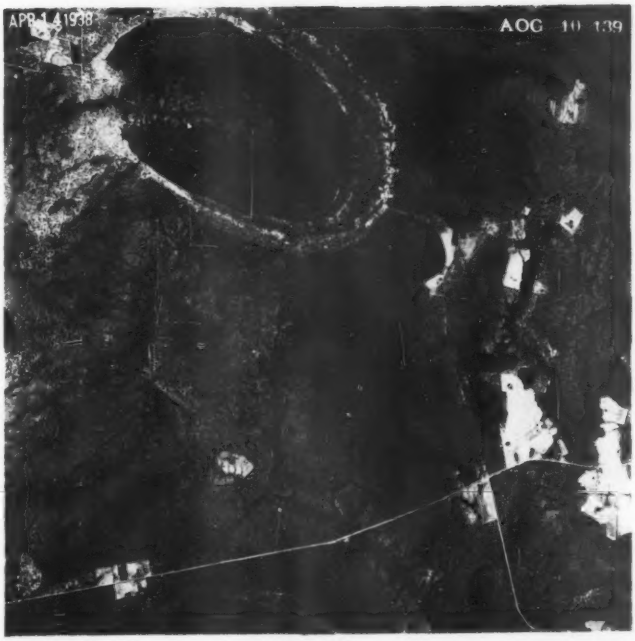


FIGURE 1

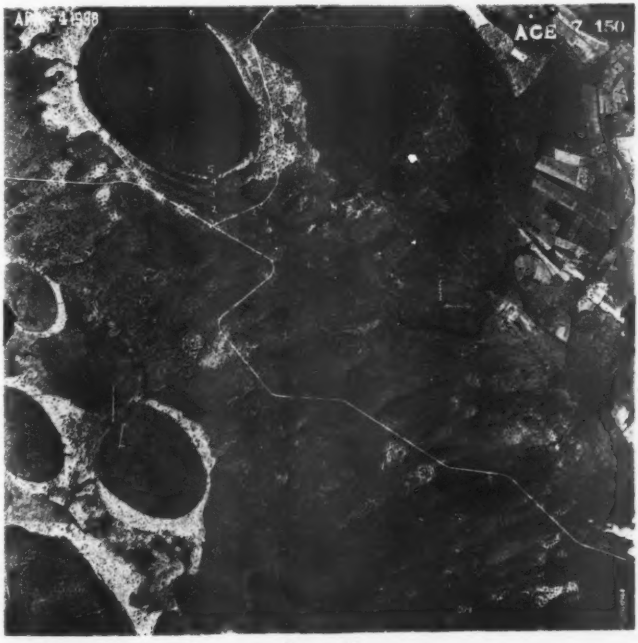


FIGURE 2

MULTIPLE BAYS IN SAMPSON AND BLADEN COUNTIES, NORTH CAROLINA

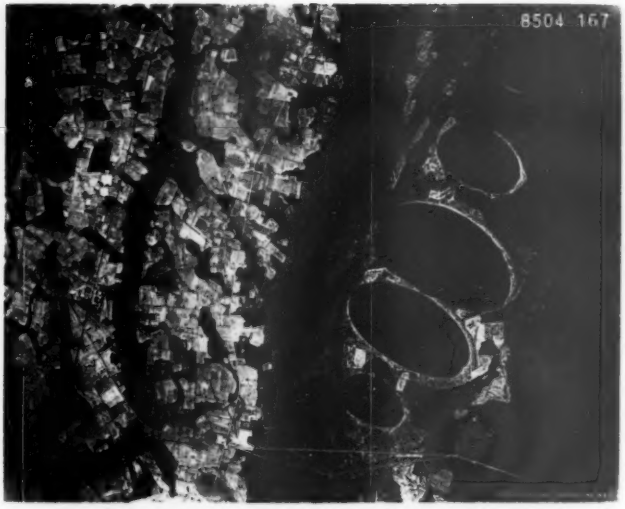


FIGURE 1. BAYS 10 MILES SOUTH OF MULLINS, SOUTH CAROLINA
(Fairchild Aerial Surveys, Inc., New York, N. Y.)
See Figure 7A for descriptive data.

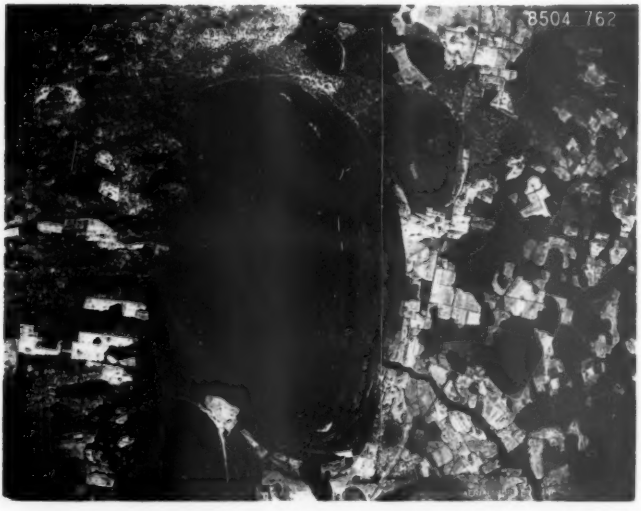


FIGURE 2. CYPRESS CREEK BAY, SOUTHEAST OF MARION, SOUTH CAROLINA
See Figure 7B for interpretive data.

BAYS IN MARION COUNTY, SOUTH CAROLINA

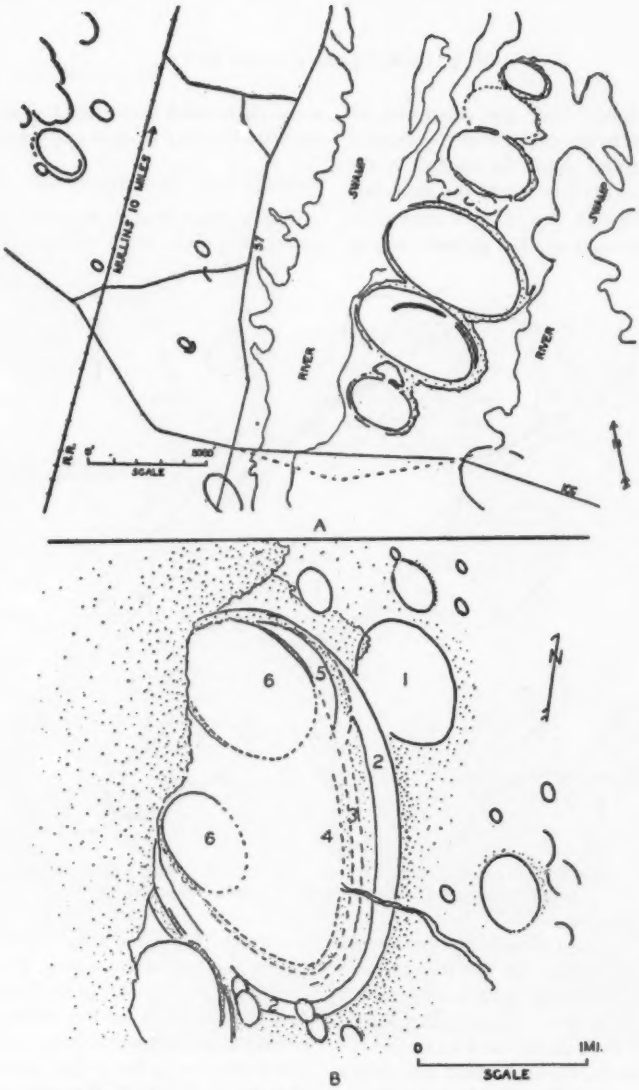


FIGURE 7.—BAYS IN MARION COUNTY, SOUTH CAROLINA

A. Group of bays about 10 miles south from Mullins, Marion County, South Carolina.

Five well-preserved bays, varying from 2000 to 8000 feet long occur side by side along a sandy area between river swamps to north and to south, and which here trend N.32°E. Long axis of bays is about at right angles to orientation of line of lineation of the bays. If these bays had been in the low ground between the two sand ridges, their position might argue for Cooke's segmented lagoon theory of bay origin, but since they occur in high ground, their position can be used against both the segmented lagoon theory and against the solution and artesian spring theories. The five bays have almost identical elongation direction.

B. Cypress Creek Bay, southeast of Marion, South Carolina.

This bay is 2½ miles long and appears to be ovate. Apparent narrowing toward southeast is largely due to: (1) cultivated land on both east and west sides of southeast end; (2) small bay on southwest side which cuts out a portion of outside rim; (3) two small bays inside outer rim which cut out some of inner rim of big bay in northeast and west sides.

An unusual amount of sand has drifted into the northwest quadrant of the bay, apparently by wind action chiefly but also by stream action. Drainage is through southeast rim where the rim was originally highest. Drainage of bays takes place where the bay is approached by a stream working headward toward the bay and at an elevation below that of the bay. This figure attempts to explain the order of formation of the large bay and its satellites.

difficult to explain from the standpoint of solution theory. In the case of origin by artesian springs, the spring would be located in the deepest part of the bay where the ascending water rising through the agitated sand picks out and carries away the fine particles or acts as an agent of solution. The deepest part would be the area from which the fine particles and material in solution were most readily carried away. In either case the fine particles should not be present between the sand below and the peat above. Again, the bays would have had a wide marsh border if they had been formed by either solution or artesian spring action. Such areas of little water-table fluctuation would give peat with marsh community plants. If the bay developed where the water table had considerable fluctuation, a shrub-bog community, according to Wells, should develop and the peat should contain pollen from such shrubs as heath, gallberries and ti-ti. Instead, we find first a wind-blown silt deposit and then peat of an aquatic nature including pollen from water lilies, which shows that the lake had deep water at the very start of sedimentation.

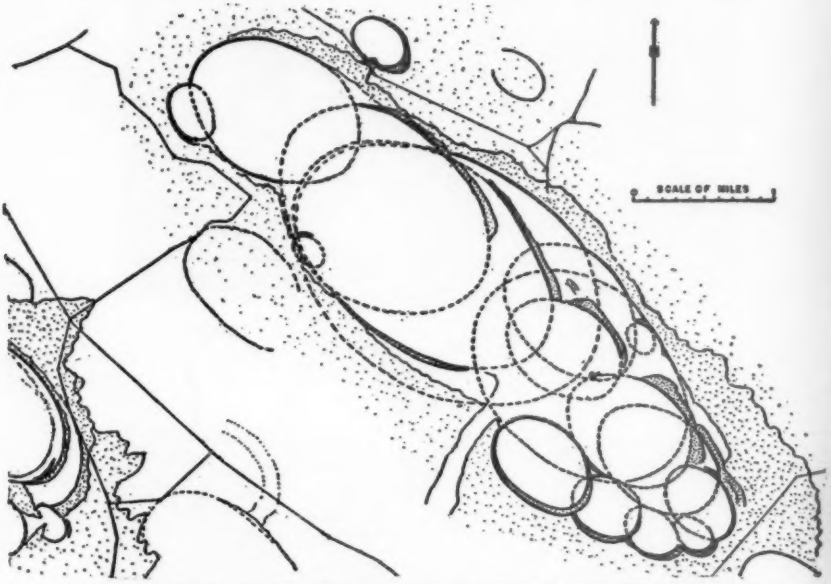
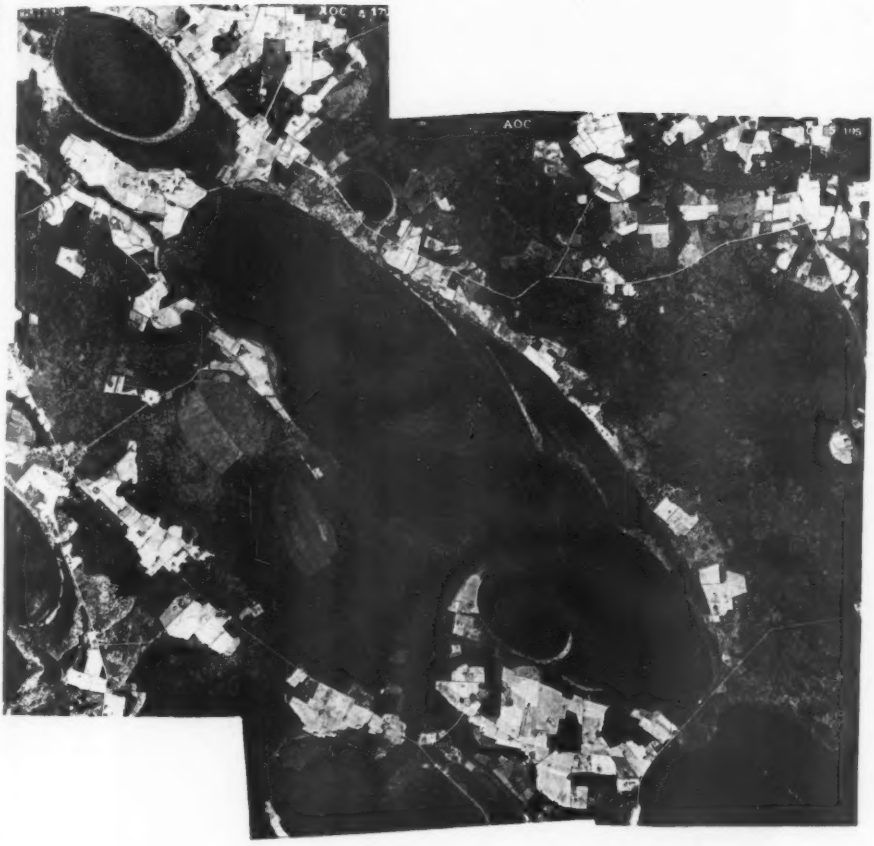


FIGURE 8.—ELONGATED MULTIPLE BAY IN CUMBERLAND COUNTY, NORTH CAROLINA
Approximately 16 bays comprise the large elongated bay.

ORIENTATION, LINEATION, AND ELLIPTICITY

The average local orientation of the bays varies from about south 55° east in the northeastern portion of the area to about south 15° east in the southwestern area. There is thus a divergence of about 40° in the elongation direction of the bays in the two extreme areas. According to the meteoritic theory as here revised, this divergence is due to the fanning-out effect of a group of bodies, the meteorites, passing through the resisting gaseous medium of the atmosphere. This would mean a maximum average divergence of only 20° on either side of the median plane. There is in all parts of the Carolina Bay area also considerable difference in the orientation of different contiguous bays. This is explained, under the revised meteoritic theory, by the sudden bursting or mild explosion of some meteorite masses as they become heated in their passage through the atmosphere before reaching the earth; also by the effect of



ELONGATED MULTIPLE BAY IN CUMBERLAND COUNTY, NORTH CAROLINA
See Figure 8 for interpretation.

OVERLAPPING BAYS, BLADEN COUNTY, NORTH CAROLINA

the partial vacuum area in the air pressure cone accompanying the fall of tandem meteorites, explained elsewhere.

The difference in orientation due to partial fragmentation of some of the meteoritic masses before hitting the Earth is logical. Those thrown to the left would travel a path different from those thrown to the right. The smaller fragments would tend to have a greater divergence from the mean path of the meteorite than the larger fragments. From the Bladen County index mosaic map, 101 bays were carefully measured and plotted for orientation; 90 bays were measured and plotted from the Robeson County, North Carolina, mosaic sheet (Figs. 10, 11). In both areas, the larger bays have much less variation in orientation than the smaller bays, as would be expected from the revised meteoritic theory. In the process of fragmentation of bursting, the smaller masses should be thrown farther from the direction of travel of the parent mass than the larger masses.

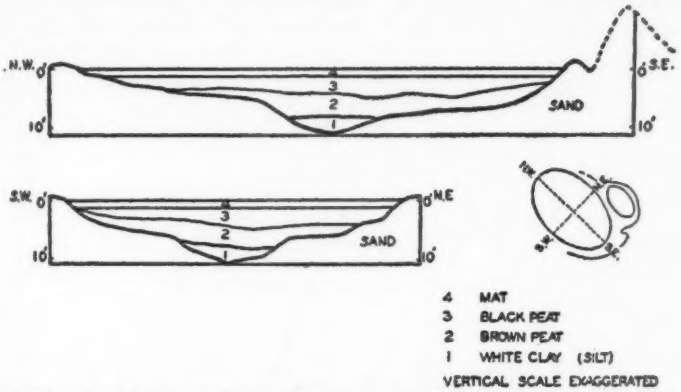


FIGURE 9.—PROFILE SECTION OF JEROME BAY, EAST OF JEROME, NEAR CUMBERLAND-BLADEN COUNTY LINE, NORTH CAROLINA
Modified after Buell (1942b).

The difference in ellipticity of the bays is equally well explained by the fanning out of of the meteorites in passing through the atmosphere and also by the fragmentation or bursting of some of the parent meteorites before hitting the earth. Such factors help determine the angle of impact and therefore effect the

PLATE 9.—OVERLAPPING BAYS, BLADEN COUNTY, NORTH CAROLINA

Large bay about 2¼ miles long has had its northeast rim cut out by formation of smaller bay to east, after at least most members of composite rim at southeast end of big bay were formed. According to meteoritic theory, these several rims at southeast end of bay were also formed by force of meteoritic action and are not a later development by wind, current, etc.

Where the smaller bay cuts the larger bay there is a well-developed rim on west side. Slumping by solution or artesian spring action should give a depression between bays, and wind and current action should not be able to build up a high rim on west side, but air-shock waves moving out from center of smaller bay would form this rim out of the sand earlier used in forming east rim of larger bay.

Little bay on west side of large bay is also younger than large bay and its small inner rim.

Northeast-southwest trending swales and broader and rather uneven low sand ridges in south and southwest are cut by bays, proving the bays are younger. In few places where sand is relatively unprotected by vegetation as in rather high and dry east rim of most western bay, sand has moved northeastward. Rim of this latter bay is unusually well developed due seemingly to its formation in an area of higher and therefore drier sand, more readily moved by air-shock waves. Even northwest rim is here well developed.

ellipticity. These differences in ellipticity may be caused by the forces acting in the vertical rather than in the horizontal plane. Another factor may be differences in specific gravity of the different meteorites. Some having a higher percentage of metal than others would be less effected by air resistance and would tend to form bays of greater ellipticity. Small meteorites, which would make smaller bays, tend to form less ellipticity than single large bays. Among the smaller meteorites, however, those having positions above the center line of advance of the parent meteoritic mass (nearer tangency to the earth's surface) would tend to form bays with greater ellipticity than those holding positions below such center line of advance.

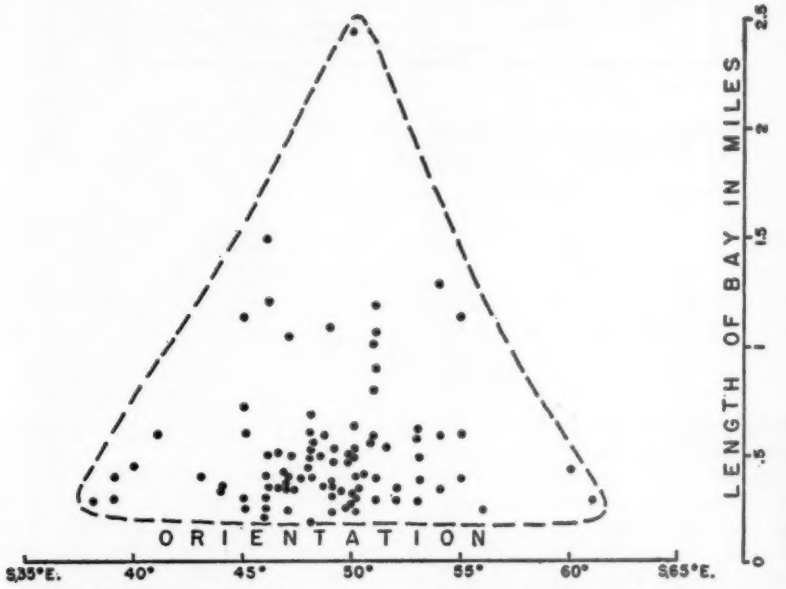


FIGURE 10.—ORIENTATION OF BAYS IN A PART OF ROBESON COUNTY, NORTH CAROLINA
Plotted against length of long diameter of bays.

Bays have been studied for their ellipticity[3] in three counties in South Carolina and one county in North Carolina. The first study was made by Melton and Schriever (1933) in the Myrtle Beach Area, Horry County, South Carolina. Later studies were made by the writer, in Marion and Darlington counties, South Carolina, and Bladen County, North Carolina (Fig. 12).

The bays studied in Horry County, South Carolina, varied from 500 feet to nearly 6000 feet long. Their minimum ellipticity is .170; the maximum, .495; and the average, .340. In Bladen County, 63 bays varying in length from 500 to 3700 feet show a minimum ellipticity of .270, a maximum of .457, and an average of .363.

Twenty-six relatively larger bays in Marion and Darlington counties, South Carolina, varying in length from 550 feet to 7000 feet, have a minimum ellipticity of .245, a maximum of .495, and an average of .420.

The 130 bays studied for their ellipticity in the three different localities in the two states have been plotted in Figure 12. The same general conclusion can be drawn from all three

[3] Ellipticity = long axis-short axis/long axis.

localities: (1) There is a variation in the ellipticity of bays of the same size with a much larger variation in the bays of smaller size. (2) In every locality the larger bays have an average ellipticity greater than that of the smaller bays.

In selecting bays for ellipticity measurements, from a bursting meteorite would be thrown into a course more at variance with that of the parent meteorite than would larger fragments. Unless the bursting of the parent meteorite occurred close to the Earth, the greater slowing down of the smaller meteorites than of the larger would, in many instances, allow the

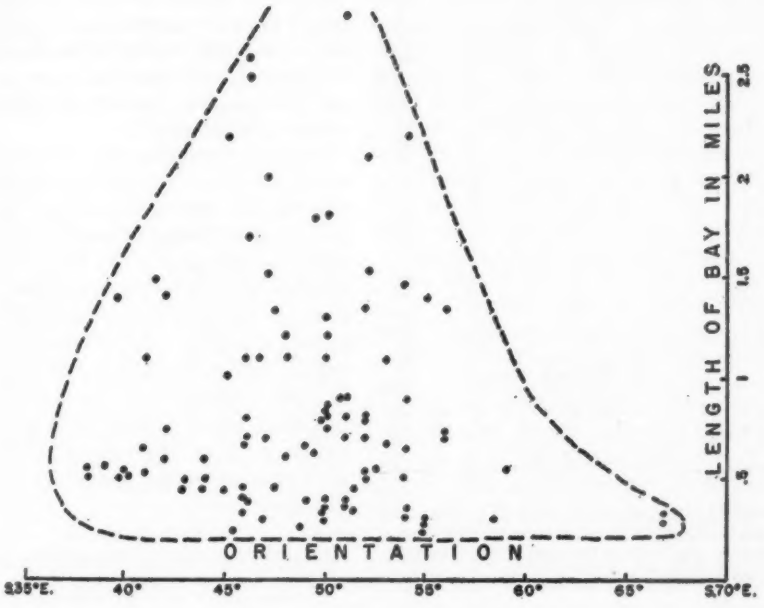


FIGURE 11.—ORIENTATION OF SOME BAYS IN BLADEN COUNTY, NORTH CAROLINA
Plotted against length of long diameter of bays.

it is essential to avoid the multiple bay, for such are either lengthened or broadened by the overlapping of one or more younger bays. One multiple bay in Sampson County, North Carolina, made up of 12 overlapping unit bays, would have an ellipticity of .700, while some of the multiple bays in Georgia are so much broadened by the more westerly overlap of the younger unit bays as to yield an ellipticity of less than .0.

As we have seen before, the smaller fragments larger fragments (travelling less curved paths) to form bays with even greater ellipticity than that of those smaller meteorites which were thrown more upward and forward by the mild atmospheric explosion of the parent meteorite.

It is noted in many parts of the bay distribution area that several contiguous or closely spaced bays may have a definite directional arrangement or *lineation* as contrasted with the *orientation* discussed above. This lineation

direction is most frequently between northwest and west. In many cases where the lineation is north of west, there is also a decrease in the size of the bays in that direction; each bay to the northwest is younger than its neighbor

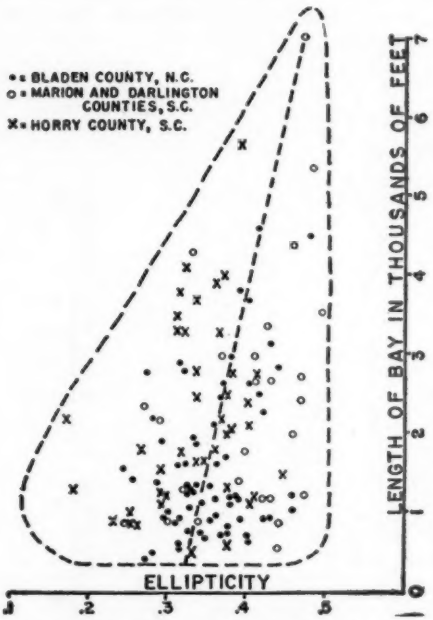


FIGURE 12.—ELLIPTICITY OF SOME BAYS IN BLADEN COUNTY, NORTH CAROLINA, AND MARION, DARLINGTON, AND HORRY COUNTIES, SOUTH CAROLINA
Plotted against length of long diameter of bays.

to the southeast; and, in many cases, the ones to the northwest have a counter-clockwise rotation of their axis of elongation. These facts are best explained by tandem meteorites hitting an east-turning earth at intervals of seconds or fractions of seconds, as explained more fully in the section dealing with multiple bays.

Douglas Johnson (1942) thought the orientation of bays is chiefly due to the interaction of the forces of rising artesian springwater and the down-slope migration of groundwater in the surficial sandy layers of the Atlantic Coastal Plain, the different orientations of the bays being due to the difference in the dip directions of the beds furnishing the artesian water and of the overlying surficial sandy layers in different parts of the Coastal Plain. On close analysis, it is found that conditions in the Coastal Plain do not allow the orientation or the lineation to be thus explained, nor can the elliptical shape or heart shape of the bays be so explained. (See section on Multiple and Heart-shaped Bays.)

The theories of bay orientation conforming with wind direction or with gyroscopic effects due to rotating Earth on confined bodies of water do not explain many of the known facts regarding bay orientation, ellipticity, lineation, age, or geographical distribution. Furthermore the laws of gyroscopic motion apply to solids and not to liquids. (See section on Objections to Terrestrial Theories.)

Lineation is frequently in a direction a little west of northwest in North Carolina (Fig. 18) and between west and northwest but more nearly west in Georgia, where the general orientation of the bays as contrasted with the lineation is more nearly north-south. These facts are explained by the meteoritic theory through a rotating earth, tandem meteorites, and varying directions of meteoritic movements in North Carolina and in Georgia. There are no present known methods of explaining the various peculiar lineations, ellipticities, and orientations of the bays except by a meteoritic hypothesis.

SINGLE, MULTIPLE AND HEART-SHAPED BAYS

Carolina Bays may be classified as single or as multiple bays. The single bay has one large elliptical rim, type 1 (Pl. 5), or one large elliptical rim and one or more smaller, crescentic, symmetrical, or nearly symmetrical, inner rims, type 2 (Pl. 6). The multiple bays are made up of two or more single bays in various combinations of types 1 and 2, by overlap. In multiple bays, the portion of the overlapped earlier bay is entirely obliterated by the later overlapping bay (Pl. 9). Most of the multiple bays are made of two single bays, but those made by a greater number are not uncommon. One multiple bay in Cumberland County, North Carolina is seemingly made up of twelve overlapping single bays (Pl. 8). Many of the large bays are multiple bays and most of the small

bays are single bays, but there seems to be no definite relationship of size to class.

Multiple bays have various shapes, caused by a hit or miss system of overlap. In many cases, however, the overlap seems to be directional, and in most of these cases the direction of the successive overlaps is either chiefly northwest (Pls. 8, 10) or largely west or slightly north of west (Pls. 7, 15).

Why some single bays have only the large outer rims and others have in addition smaller, symmetrical, crescentic inner rims, has been a difficult question to answer. These inner rims are best developed toward the southeast end of the bays, and, because they are usually less elliptical than the outer rims, they usually connect with the outer rim in the northwest half of the bay.

Since both the larger outer rim and the smaller inner rim, or rims, have approximately the same symmetrical relation to the plane of symmetry of the long axis of the bay, it seems logical to assume that both these types of rims were formed by the same originating forces.

In the western portion of the "bay country," where the general direction of elongation of the bays is a little nearer south than southeast, there are many heart-shaped (Prouty, 1948) multiple bays, usually made up of two single bays of nearly the same size, the overlapping or later-formed unit being to the west and a little to the north of the earlier-formed unit. The overlapping unit usually has its direction of elongation turned slightly counter clockwise in respect to the elongation direction of the earlier formed bay. This causes a general southeast convergence of the long axes of the overlapping bays (Fig. 28; Pl. 11, fig. 2). In a few cases the convergence of the long axes is in the opposite direction. Significance of the multiple and heart-shaped bays will be discussed later.

Age of Carolina Bays

The Carolina Bays are found on all the Pleistocene terraces from the oldest along the inner edge of the Coastal Plain to the Pamlico, which is the youngest and the lowest terrace. They are observed in some instances along flood plains of streams breaching the terraces (Pl. 4). If we assume terrestrial processes to be responsible for the formation of the bays, such as solution, wind and wave, submarine scour, rotary current, artesian springs, or "shoals of fish", then the age of the bays should range in every case all the way from early Pleistocene to the present. Bays on higher ground, whether inland or near the coast, should be older than those on lower ground, and they should extend well down to the coastline and have wide geographical distribution. Also, bays should be in the process of formation at the present time.

According to the meteoritic theory of bay origin, on the other hand, the Carolina Bays should be of practically the same age wherever they are found. Bays formed in higher and drier areas should have better developed time. Any bays formed in the shallow sea of the time, or later temporarily covered by the sea, should be considerably modified, and if not completely destroyed and still recognizable, should have the appearance of greater age than other bays.

A paper by Buell (1946a) places the age of Jerome Bay, Bladen County, North Carolina, as late Pleistocene, as it has yielded but one zone of cold climate flora. If this assignment is correct, the fact that this bay rests on the surface of one of the older Pleistocene terraces supports the meteoritic theory. However, the observed facts do not necessarily prove the accuracy of the age assigned, since a study of the peat profile published by Buell (1946) shows the presence in the peat of an abundance of charred plant fragments and quantities of fine charcoal in the upper half of the peat deposit. If this deposit had shown a succession of warm and cold climate flora having the correct sequence of climate changes for the particular terrace on which it occurs and if other bays on other terraces showed similar correspondence with their respective terrace age, it would be an argument against the meteoritic theory; but the absence of such a sequence when peat fires are clearly indicated, as in Jerome Bay, does not prove that such sequence did not occur.

In many places in the lower lands near the coast, indicated on aerial photographs, bays continue almost perfectly preserved up to an apparent ancient shore zone, but seaward from this zone and toward lower elevations, bays are either largely or possibly completely blotted out by either erosion or sedimentation. Such a dividing line between well preserved bays and poorly preserved bays can be seen about 7

miles northwest from the town of Myrtle Beach, South Carolina. From this line oceanward, beach ridges and bays are either poorly preserved or absent, although in the opposite direction, inland, beach ridges and swales with numerous bays occur for several miles (Fig. 21)[4]. Melton and Schriever (1933) state the obvious fact that the bays, if they are of meteoritic origin, must be no older than the youngest formations in which they occur. These bays clearly cut beach ridges developed on a late Pleistocene terrace (Pl. 3, fig. 2). Therefore, the bays cannot be older than late Pleistocene if formed by meteorites. Many bays lying at low levels near the coast have been flooded and largely or entirely obliterated, but those formed on higher ground (most bays) have apparently never been covered by the sea.

Figure 19 shows three bays, X, Y, and Z, in relation to three distinct temporary shore lines: M-N the oldest, A-A′ of intermediate age, and B-B′ the youngest. It also shows relation of the bays to beach ridges 1, 3, 5, 7, 9, and swales 4, 6, 8, and 10. Bay X is younger than shore line M-N which it transects. It also was present

[4] Figure 21 is after Douglas Johnson (1942, Fig. 11, p. 53) and Melton and Schriever (1933, Fig. 6, p. 58).

PLATE 10.—SUGGS MILLPOND BAY, BLADEN COUNTY, NORTH CAROLINA

This multiple bay is composed of three single bays; each successively younger bay is smaller than its predecessor, and each is more to the northwest and a little more to the west—the ideal from the infall of three tandem meteorites of decreasing mass. The size of the second bay and the fact that the second meteorite fell but a little back of the first indicates that it was apparently only a little smaller than the first, and that the time interval between the fall of the two was so short that there was little westward shift due to rotation of the earth. Crowding of first rim by the second precludes observation of possible secondary rims associated with older bay. The third meteorite was considerably smaller than the second. It therefore fell farther northwest and was carried farther west by earth's rotation. To the east and south can be seen two secondary rims belonging to the second-formed single bay. Rim of older and larger bay was barely overlapped by later bays on northwest side, owing to smaller size of successively formed bays.

Four older and smaller bays were overlapped by Suggs Millpond Bay. Border rim is formed across each of four overlapped bays, including the one toward the northwest. It is difficult to explain such rims by any theory other than meteoritic.

Suggs Millpond Bay has bottom springs near southeast end similar to those in White Lake Bay. Active springs in bay lakes not common although they should be expected if penetration by meteoritic matter is deep. Such springs should also logically be at southeast end of bay. Dam across natural bay outlet, on south side, has raised the water in the bay, thus emphasizing delta-built peninsula extending northwestward to former overflow point from the next bay to the northwest. This overflow seemingly occurred when water table was higher than now.

PLATE 11.—BAYS IN BRUNSWICK COUNTY, NORTH CAROLINA, AND SCREVEN COUNTY, GEORGIA

FIGURE 1.—BAYS IN BRUNSWICK COUNTY, NORTH CAROLINA

Several of these were formed in low land which has since been under water and considerably eroded. The largely obliterated bays, such as C 1–6 and E 1 and 2, are called "ghost bays". In higher ground toward south and west bays have been eroded less. Several are multiple bays. At *A* the three parts of the bay were formed in the order A 1, A 2, A 3. A 2 has a larger rim than A 1 and is turned counter clockwise about 10° and set back toward northwest about a third of the length of A 1. A 3 is smaller than A 2, is set back toward the northwest only a small amount, and is very slightly turned counter clockwise from A 2. B 1 is toward northwest; B 2 is smaller and toward southeast; B 3 is between B 1 and B 2. "Ghost bays" C 1–6 are numbered from oldest to youngest. Overlaps here seem haphazard, as distinguished from chain or tandem type of multiple bay in which a definite direction of overlap is accompanied in most cases by slight counter clockwise turning of direction of long axis in the younger elliptical depression.

FIGURE 2.—HEART-SHAPED BAY IN SCREVEN COUNTY, GEORGIA

About 45 miles southeast of Augusta. Original rims of all the bays are largely modified by overwash. Careful examination of large bay suggests it is made of two unit bays, the eastern unit having an orientation of S 8° E., the second is farther west and turned to about S. 24° E. The bay just east of the large multiple bay has an orientation of S. 34° E.

SUGGS MILLPOND BAY, BLADEN COUNTY, NORTH CAROLINA

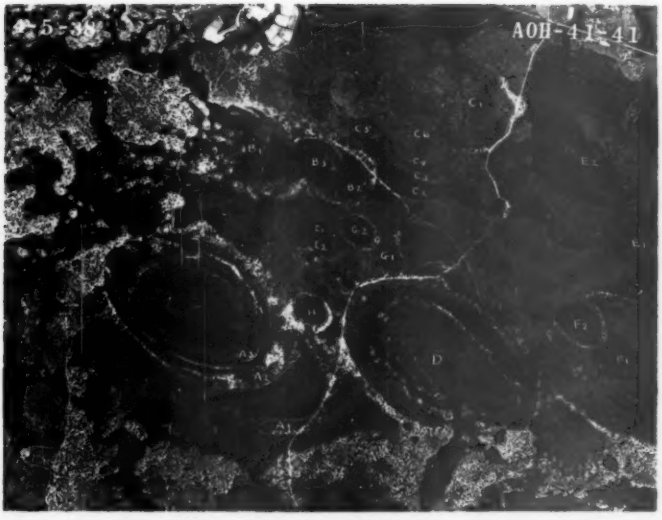
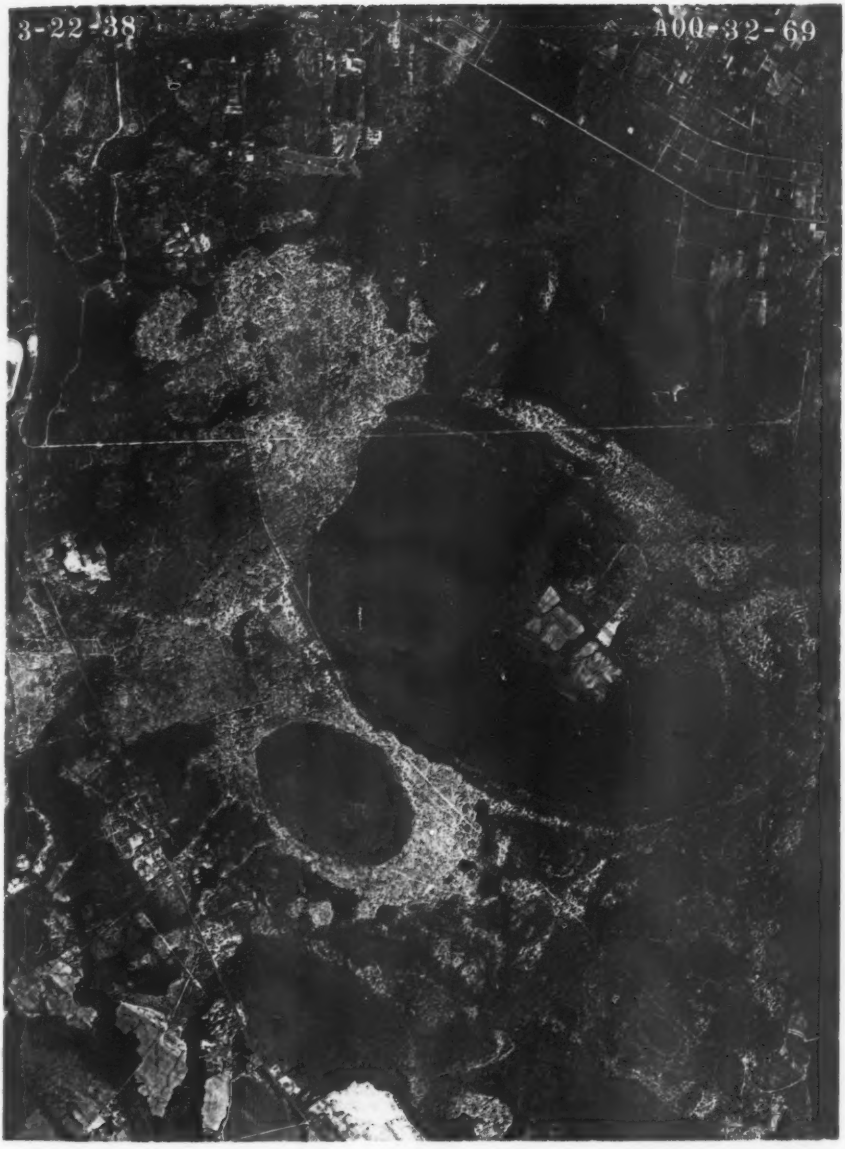


FIGURE 1

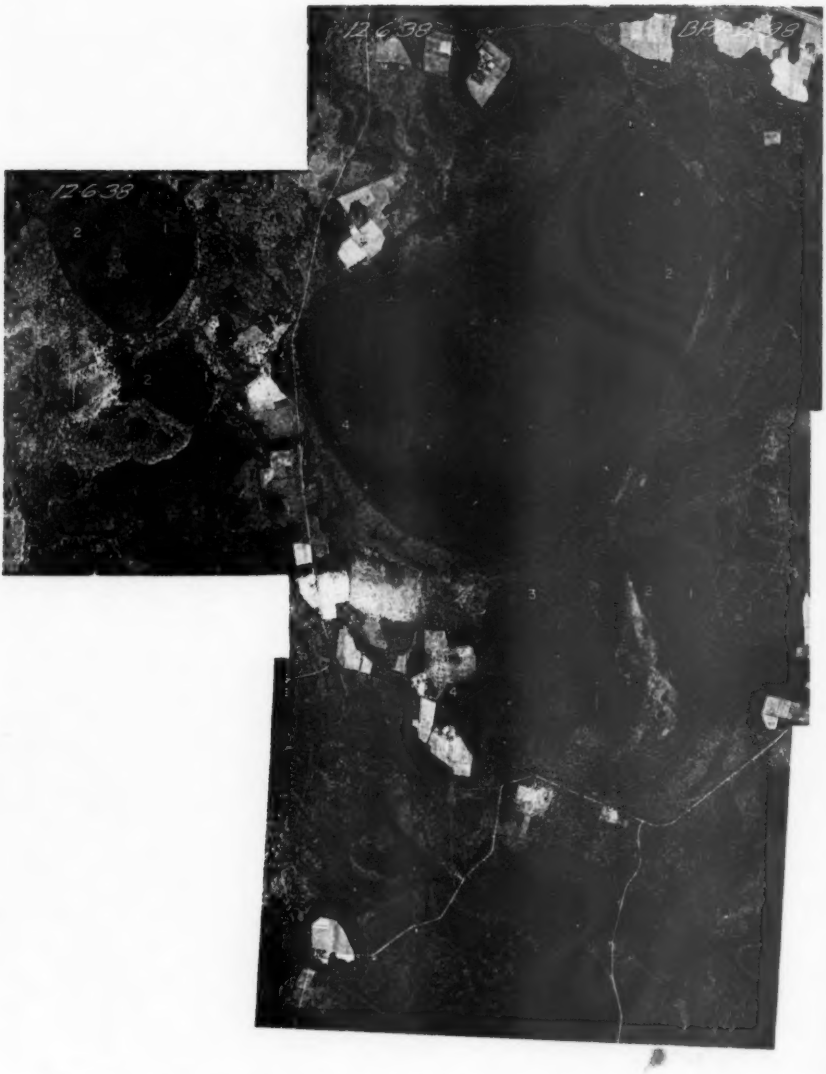
FIGURE 2

BAYS IN BRUNSWICK COUNTY, NORTH CAROLINA, AND SCREVEN COUNTY, GEORGIA



BLYTHE BAY, NORTH CAROLINA

This bay (about 3 miles southeast of Wilmington, North Carolina) is about 50 feet above sea level and drained by stream extending 2 miles to the ocean. Along stream overlying peat filling, 7½ feet of marine sediment is exposed. (*See* Flooding of Near Coast Bays.) Northwest end of bay has been filled to a maximum width of about a fourth of a mile by fine-textured dune sand which rises to a maximum height of 20 feet above the level of the bay, along east-west road crossing north end of bay. Small inner rims indicate that two smaller bays are largely concealed inside larger and older rim. One is the narrow rim cut by the road in north part of bay; the other is partially concealed by delta toward southeast end of bay.



MULTIPLE BAYS IN ATKINSON COUNTY, GEORGIA
See Figure 13 for description.

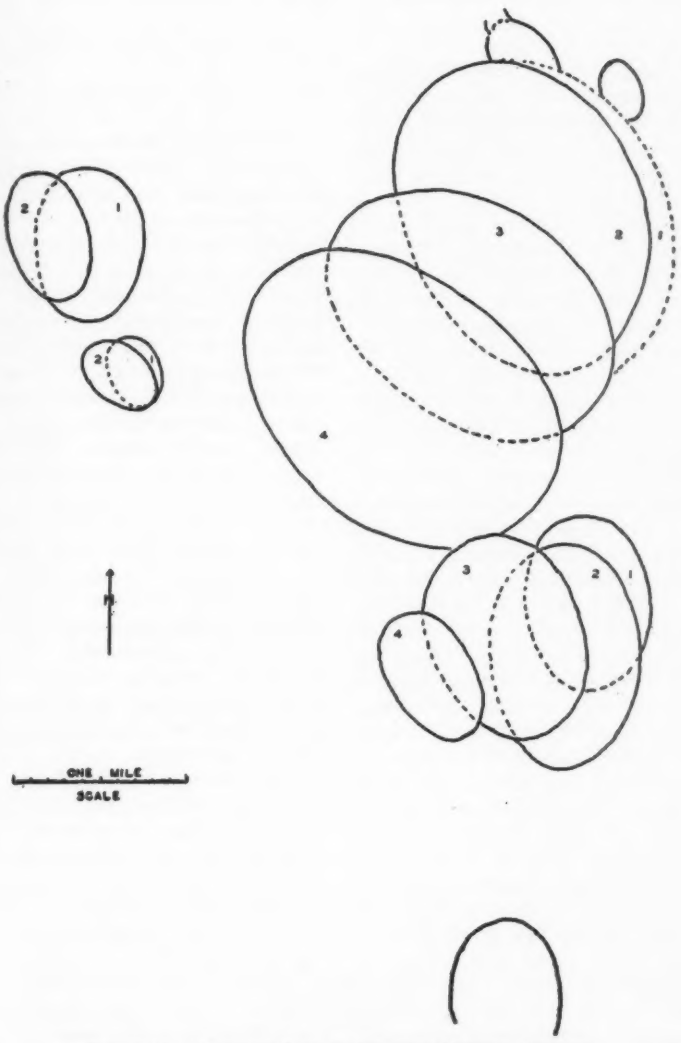


FIGURE 13.—MULTIPLE BAYS IN ATKINSON COUNTY, GEORGIA

Largest of the four multiple bays in this area is about 3 miles long and composed of four separate, overlapping elliptical depressions. Directly south of the large bay is a multiple bay of medium size composed also of 4 overlapping elliptical depressions. To the west are two smaller multiple bays, each with two overlapping elliptical parts. In each bay, the unit or units to the west have a smaller azimuth of orientation of the long axes than do the units on the east side.

for a period after the formation of bays Y and Z, as is shown by their partial destruction by wave action and the construction of faint swales 4, 6, 8, and 10, and faint beach ridges 5, 7, and 9 across them. The ocean front must later have moved from A-A′ to B-B′ and remained long enough to complete the destruction by wave action of the southern ends of the bay Z.

The general interpretation of this figure according to the meteoritic theory of bay origin is: Bays X, Y, and Z were formed after the withdrawal of the shore line from M-N. At time of bay formation, the shore line was either at A-A′ or farther toward the southeast. If the shore line was at A-A′, bays Y and Z were formed in shallow water. This condition lasted long enough for bay rims to be partially destroyed and for two faint beach ridges and two shallow swales to be formed as the water gradually withdrew. The retreating shore line made another pause along B-B′. Here the ocean stood long enough to almost completely destroy the rims at the southeast ends of bays Y and Z. The other interpretation of the conditions of sea movement is that the sea withdrew completely from the area of the picture before the bays were formed and later returned to the line A-A′, then gradually retreated, pausing for a while at B-B′.

If we assume the meteoritic theory, therefore, bays X, Y, and Z are all younger than shore line M-N and older than shore line B-B′ and the poorly developed beach ridges and swales 4, 5, 6, 7, 8, 9, and 10. If bays Y and Z were younger than the shore line B-B′ and the associated minor swales and beach ridges, which they should be if formed by ordinary terrestrial forces such as wind, solution, and artesian springs, these bays (Y and Z), being younger, should be as well preserved, if not better preserved, than bay X. It is obvious that the age of the bays is between M-N′ and B-B′ time, and that the meteoritic theory of origin is favored.

It may be contended that, after the formation of beach ridge 1, the sea steadily withdrew for some distance and that bays X, Y, and Z and others were formed on the newly emerged terrace and that, further, these were partially or wholly destroyed by a resurgence of the sea to shore lines A-A′ and B-B′. In that case, when the sea finally withdrew and again left an emergent marine terrace, this area should, according to the terrestrial mode of origin of bays, have well shaped bays developed on it. This is not the case. Whichever theory we assume about the movement of the ocean, whether a simple withdrawal from line M-N or a withdrawal followed by a resurgence to line A-A′ and a later withdrawal, the facts favor the meteoritic theory of origin and a time of formation later than the emergence of most of the Pamlico or latest marine terrace of Pleistocene time.

Bay Sinks

Dr. Douglas Johnson (1936b) has made a detailed study of depressions, chiefly in South Carolina, which show characteristics of both sinks and bays. All the cases cited by Johnson, as well as the cases studied by the author, show the changes to be taking place in one direction: bays to sinks and not sinks to bays. The writer has long recognized this fact and has called such depressions "bay sinks" (Prouty, 1935). In a number of cases the active changes going on at the present time can be readily studied. Such change is most active where a gully is eroding headward in the direction of the bay. When such a gully has its head lower than the water level in the bay, percolation becomes more active and water moves underground from the bay-swamp toward the stream head with attendant underground solution and the slumping ing and final breaching of the bay sand rim. This action more often occurs from directions other than from the southeast end. Usually the lake or swamp is partially drained by this action. Green Savannah Lake (bay), Allendale Quadrangle, South Carolina, furnished a good example of such change.

Bently Branch is approaching Green Savannah Lake by headward erosion at a point a little west of the northwest end of the bay and at a level below that of the surface of the lake in the bay; as a result, the bay is being elongated and the rim lowered by the solvent action of groundwater movement from lake to stream head. It is being changed from a typical rimmed bay into a sink. As a result of the underground seepage, a gap is forming in the northwest rim which in the course of time will become a stream valley. The lake and swamp level is already between 20 and 30 feet below the sand rims. It therefore could well be classed as a sink.

This type of depression is properly classified as a "bay sink." Other noteworthy examples may be observed near Adel and Cecil, Cook County, Georgia (Fig. 20). Many of the lakes have been altered so that only small remnants of their original elliptical shapes remain.

Sinks Not Confined to Limestone Areas

Solution depressions may be developed by solution of iron or other slightly soluble materials and not always by the solution of limestone, as Smith pointed out (1931).

Wherever water accumulates in shallow depressions and slowly drains away through percolation there is solution, varying with the solubility of the local earth minerals. No mineral is entirely insoluble. Movement of colloids in underground waters may cause shallow depressions. In areas where kaolin deposits are forming, the finer clay particles tend to migrate from the steep slopes and accumulate in the flatter areas at the foot of these slopes. The clay substance contained in kaolin deposits shows a large increase in down-slope localities. In some areas of kaolin occurrence in western North Carolina, lens-shaped deposits of kaolin with rather high clay (kaolinite) content are found on the higher stream terraces. Where groundwaters drain from these lenses, they are often milky white. In places such deposits have suffered a "slump" due seemingly to the loss of large quantities of colloidal material from these buried kaolin lenses. All such depressions should be classified as sinks because they have been developed through loss of soluble or colloidal material and a consequent lowering of the surface. Such sinks do not tend to develop sand rims, a feature so common in the Carolina Bays.

Flooding of Near-Coast Bays

Evidence of oceanic flooding of the bays is to be seen in many near-coast localities in the Carolinas. Attention was called to this by Melton and Schriever (1933):

> "Not only have the depressions been obscured and their rims partially removed by wave and current action, but there are a few features visible on the mosaic to be explained only as basins which have been completely filled and buried by the beach material along this old shore" (Figs. 19, 21; Pl. 17).

Figure 19, showing good examples of flooding, has been discussed earlier. Plate 17 shows partial inundation of a multiple bay near Myrtle Beach, South Carolina. Figure 21 shows the same general area and the apparent effects of fairly recent flooding on beach ridges and bays.

Ashe's Creek Bay located in Holly Shelter in Pender County, North Carolina, has a present surface elevation of about 27 feet. There is evidence that the sand rim, which stands several feet above the bay elevation, was entirely covered by peat and marine sediments before the lowering of the ocean level or during a temporary flooding of the area by the ocean. The rim has been exposed by stream erosion. According to Wells (1943), Blythe Bay (Pl. 12) located just east of the highway connecting Wilmington and Carolina Beach, North Carolina, seems to show a change of sea level in recent geological time. The stream which drains the bay cuts through about 5½ feet of peat at the bottom of the narrow valley. This is covered by 5 feet of plastic clay and this in turn by 2½ feet of fine sand. The character, distribution, and topography of the 7½ feet of sediment overlying the peat clearly demonstrate that it is a delta-like formation brought in from the east side of the bay after the bay rim had been breached. If sea flooding (since the formation

Figure 14.—Multiple Bays in Allendale County, South Carolina, and Cumberland County, North Carolina

A. Multiple bay in Allendale County, South Carolina.

This multiple bay is composed of six overlapping unit bays numbered from oldest to youngest. Each successive or younger bay is smaller than its predecessor. Bay no. 3 has two secondary rims, and Bay no. 4 has one secondary rim; all others have primary rims only. All bays have an orientation less in azimuth than that of the largest and earliest bay, no. 1.

Several of the smaller bays seem to be made up of two unit bays. The multiple bay cut by north border of picture seems to follow the tandem arrangement.

B. Multiple bay in Cumberland County, North Carolina.

The large multiple bay near the center is composed of several overlapping units. Units 1–4 are of decreasing size and are offset successively to the west and slightly to the north. They are explained as made by the infall of four tandem meteorites hitting in rapid succession an east-turning Earth. Bays 1a, 5, and 6 were unrelated infalls. The stream which drains multiple bay 1–4 from its northwest end turns eastward and passes through bay 7 which is considerably lower than bay 1–4. Multiple bay 1–4 has been partly filled with drift sand from the west.

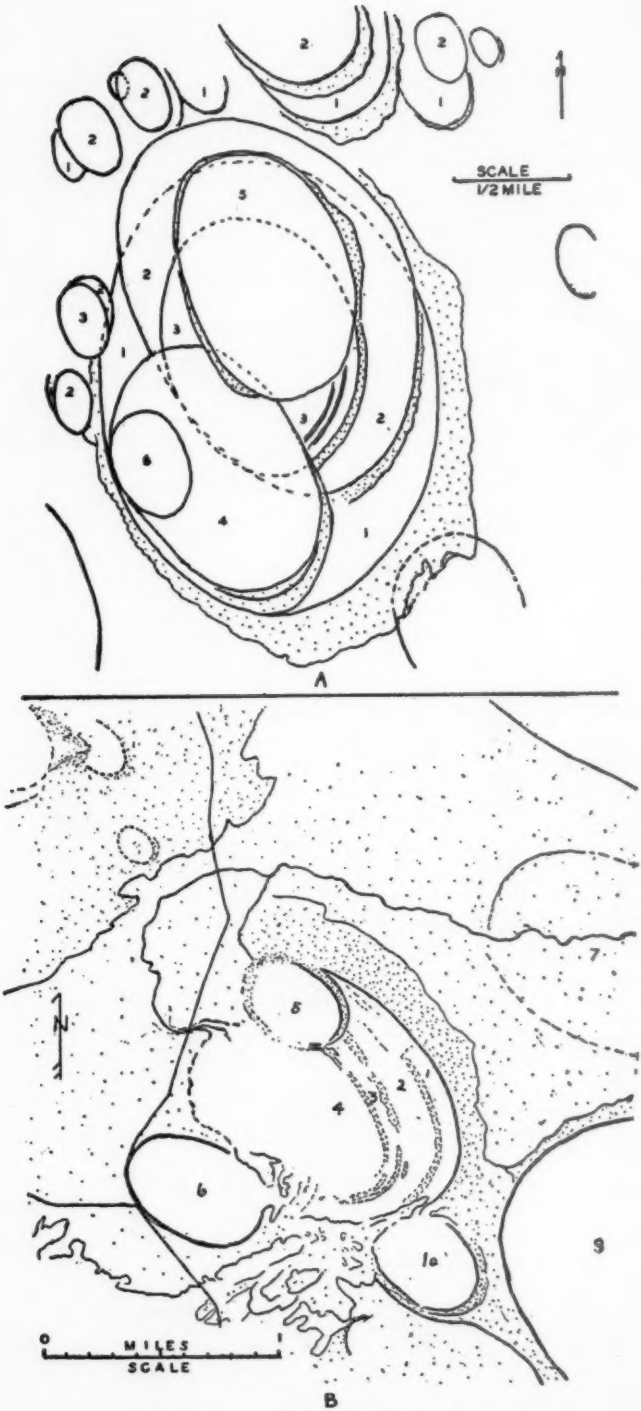


FIGURE 14—(*See* page 195 for caption.)

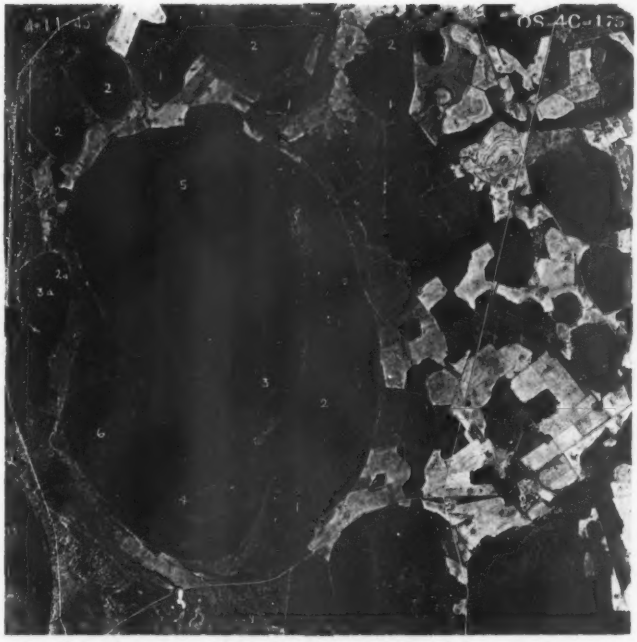


FIGURE 1. MULTIPLE BAY IN CUMBERLAND COUNTY, NORTH CAROLINA
See Figure 14A for interpretive data.

FIGURE 2. MULTIPLE BAY IN ALLENDALE COUNTY, SOUTH CAROLINA
See Figure 14B for descriptive data.

MULTIPLE BAYS IN CUMBERLAND COUNTY, NORTH CAROLINA, AND ALLENDALE COUNTY, SOUTH CAROLINA

HEART-SHAPED MULTIPLE BAYS IN ATKINSON COUNTY, GEORGIA
See Figure 15 for interpretive sketch.

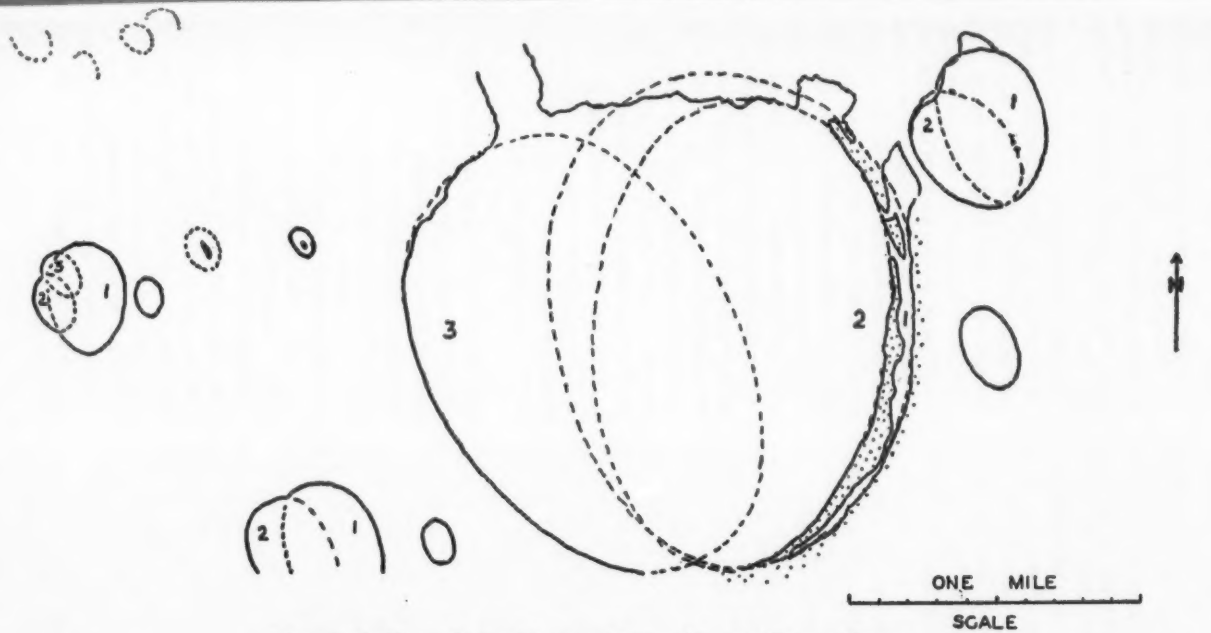


FIGURE 15.—HEART-SHAPED MULTIPLE BAYS IN ATKINSON COUNTY, GEORGIA

This large bay is nearly 2 miles in both north-south and east-west dimension, and is composed apparently of three overlapping bays, all nearly the same size. The first one, slightly larger than the other two, forms the outside eastern rim and is elongated N.6°W. The second depression, slightly smaller than the first and with north-south elongation, forms the eastern inside rim. The third is slightly smaller than the second and forms the western rim of the bay. It is elongated N.27°W. All three units have more overlap toward the south than north, owing to their southward axial convergence. This large multiple bay has been partially filled by water from the north. To the east, several areas on Plate 15 suggest bay origin. Two of these are shown here. The one to the northeast appears to be a two-unit multiple bay; the western unit has the smaller azimuth of direction of elongation. West of the large multiple bay are several "Ghost Bays", some almost obliterated by erosion and filling. However, in many cases enough of the rim can be seen, or differences in the soil color or in the vegetation show elliptical areas with characteristic bay orientation. Two small "ghost bays" in the west central part have remnant lakes (very dark area). Two bays, one about a mile west and the other about half a mile southwest of the large bay, are both multiple bays. The one to the southwest is formed by the overlap of two units, the one to the west by the overlap of three units.

of the bays) proved to be correct—as thought by Melton and Schriever (1933) and later by both the author and B. W. Wells, independently—a reasonable explanation is offered for the hundreds, if not thousands, of partially filled or largely obliterated elliptical rimmed depressions occurring in the near-coast area of the bay country. Since Blythe Bay is at present about 50 feet above mean sea level, there must have been a differential movement of this much since flooding, whether the actual movement was done by the land, or sea, or combination of both.

Critical Study of Terrestrial Theories

Wind and Current Action Theory

C. W. Cooke (1933) maintained that the elliptical, sand-rimmed depressions owe their shape to waves and currents in shallow inlets and swales, set in motion by strong winds from the southeast; that the rims were built as beach ridges and sand bars; and that the orientation of the long axes of the bays is parallel with the supposed strong southeast wind. Later, Cooke (1934) elaborated on this theory, drawing illustrations from the Myrtle Beach area, South Carolina. A series of continuous and connected bays aligned with the local swales and beach ridges was cited as originating from segmentation of the lagoon by wind, wave, and current, the contention being that all bays must originate in the shallow water of the swales and lagoons between the beach ridges. Unfortunately for this theory, the aerial photographs of his chosen group of bays shows one bay which cuts across two swales and the beach ridge between them. In the same area also, many of the larger bays cut across several swales and ridges and many of the smaller bays are found entirely on the higher group between swales. Outside of this very limited area which is near sea level, bays are as likely to be found on "high ground" as on "low ground", perhaps more likely.

Douglas Johnson (1934) advocated the formation of the bays by directional wind action on pre-existing lakes aided by the associated wave action. This process did not involve any change in level of land or sea. Later (1936a) he added that variable winds were helpful in forming the rims, and that the orientation necessitated the maximum wind from the southeast. He agreed with Cooke that the pattern of the beach ridges had influenced the distribution of the bays and that the bays were later than the beach ridges.

Following extensive field work in the Carolina Bay country, Johnson (1936b) concluded that the Carolina Bay depressions were chiefly formed by the work of solution and the consequent slumping of the overlying sand. The elongation of the bays was in the direction of the movement of ground water (down slope). Wind and wave action perfected the symmetry of the bays and built the rims from the beach sand which was blown away from the lake mainly toward the southeast rather than, as he believed formerly, from the southeast.

After further study, experimentation, and discussion, Johnson (1937) concluded that neither wind and wave action alone or wind and wave action combined with solution, adequately accounted for the origin of the Carolina Bays, but that the action of artesian springs, modified by ground water movement, does supply a force which, added to wind, wave, and solution, satisfactorily explains the presence of the Carolina Bays and their peculiarities.

Cooke (1940) abandoned the strong southeast wind as the chief cause of bay orientation and considered rotary currents in bodies of water produced by waves originating from wind action from any direction as the prime cause.

Edwin J. Raisz (1934) observed development of oval and rounded lake basins in glacial outwash plains by normal shore-line wave and wind action and suggested the same possible origin for the elliptical bays.

Several scientists in their initial study of bays have thought that wind and wave action might be the chief causes of the origin of the bays. Most of these scientists, after further study, have abandoned the idea of wind and wave action as the chief originating forces.

At the present time no one advocates wind and current action alone as the chief agents in bay formation.

Rotary Current Theory

C. W. Cooke (1940) abandoned the strong southeast wind as the chief cause of bay orien-

tation. He stated that bays originate through the action of rotary currents in bodies of water, because of an innate tendency of rotary currents in the Northern Hemisphere, to flow in ellipses whose major axes are north 45° west. He (1943) attempted to prove this theory by the resolution of the forces acting on a drop of water in an eddy, as a result of its own rotary motion and the rotation of the Earth. He seems to think that bays which lack bilateral symmetry and/or deviate from the 45° orientation must have "had a history somewhat different from that of elliptical bays." Later Cooke (1945) illustrated by aerial photographs bays "which the compass shows to be exactly northwest-southeast." Two of the bays pictured and described in this article are markedly unsymmetrical and one has an orientation 8° from the required 45°. The article seems content to overlook the fact that in a large part of the "bay country" the direction of elongation of the bays is up to 20° different from that prescribed by the rotary theory to say nothing of its inability to account for their limited geographical and time distribution.

Objections to Solution as a Prime Factor in Bay Formation

Anyone familiar with limestone-sink topography might at first be inclined to favor the solution theory of origin of any more or less circular, elliptical, or ovate depression, but after careful study of the facts related to these bays, the solution theory for the origin of Carolina Bays becomes untenable. Some objections to solution theories follow:

1. Solution is taking place in all regions where there is circulation of underground waters, yet the Carolina Bays occur only in a restricted Coastal Plain area. Many coastal plains have similar ground and water conditions but no elliptical sand-rimmed bays.

2. Bays are as well developed in noncalcareous or slightly calcareous areas as in limestone and marl areas, and as well developed near sea level and late Pleistocene as in the higher and geologically older part of the Coastal Plain, despite the fact that cavernous conditions develop best in higher limestone areas.

3. If solution is the chief factor in origin of bays, those located on higher ground should in general be larger and deeper because of the increased activity of underground waters. Also, those farther inland should be larger because they have had a longer time to develop. There seems, however, to be no rule in regard to the position of the large or the small bays.

4. Limestone sink lakes in western Florida are locally formed along joint planes of the several different joint systems. The lakes thus have varying shapes and orientations. Their sink character is evidenced by their lack of typical sand rims.

5. The strike of the more soluble limestone beds and lenses in the Coastal Plain of the Carolinas is generally northeast-southwest. One would expect the bays to be aligned in the same direction, as well as the individual elongation of each bay. Such alignment is rare and no individual bays show this elongation direction.

6. Where joint systems are prominent, solution tends to follow such directions. In the Atlantic Coastal Plain, joints trend generally northwest-southeast and northeast-southwest. Here, as in the Sarasota, Florida, area (Pl. 19), solution depressions should be arranged along joint planes in one or both directions and elongation of depression should correspond to the joint direction.

7. Bays are sand-rimmed; sinks are not sand-rimmed.

8. Some bays are formed completely inside other bays, while some of the elongated or peculiar shaped bays are made up of a number of overlapping rimmed bays (Pl. 6, fig. 1; Pl. 8).

9. Where several bays overlap and are thus of different age, there is often no uniformity in the direction of progression of this overlap. In a number of cases, the newer bay is northwest or west from the earlier bay. In others, it may be northeast, south, or west. The direction seems to be "hit or miss."

10. If bays are elongated by underground solution and caving, chiefly in a southeast direction, then the sand rims on the southeast should be destroyed by this process. They are in reality best developed there.

At the present time, many of the bays in the limestone areas of South Carolina and Georgia

are being greatly modified by the action of solution. In many cases the bay rims have been completely breached by this underground water movement. Other bays are in various stages of being breached and drained by this type of action (Fig. 20).

11. It has been pointed out that a considerable portion of the areas of certain bays is known to have an undisturbed floor. Such would not seem to be possible if the depression is due to solution and slumping. On the other hand, the meteoritic theory makes this possible when we recall that the shallow elliptical depression is the result chiefly of the wind action associated with the fall or a meteorite or meteorites which bury themselves in a restricted portion of the shallow "air-shock wave" crater. Also, if we assume that the bays are chiefly formed by the air-shock waves of the falling meteors, we have a reasonable explanation of the limitation of the bays to the sandy areas where violent wind action would be many times more effective than it would be in clay soil areas, and the sand rims once formed would be infinitely more resistant to water erosion than would any rim made of fine-textured clay. Meteorites, on the other hand, would be much better preserved buried in clay than in sand. It is interesting to note in this connection that the area of greatest meteorite occurrence is to the northwest of the Carolina Bay region (Fig. 1).

12. Southeastwardly from Conway, South Carolina, toward Myrtle Beach, a large number of perfectly preserved bays occur up to a certain beach ridge about 7 miles northwest of Myrtle Beach. Along this former beach line, at least three bays have their northern parts well preserved but their southern parts are practically destroyed, seemingly, by wave action (Fig. 19). The evidence indicates either that these bays were formed when the ocean was present in the southern portion of their area and were practically destroyed by the work of waves and currents, or that the ocean made a temporary advance into the southeastern portion of the bay area and largely destroyed all bays in the area between the present shore line and the older shore line referred to above. In either of these cases, the area between the line of old beach ridges and the present shore line should have developed bays with the departure of the ocean, if the solution theory is true.

13. Meteorite craters theoretically should promote solution by puncturing impervious beds and allowing water to rise more readily into the depression or more readily drain from it. Along the Inland Waterway near Myrtle Beach, two small bays are sectioned by the Canal. These are typical bays, though small, and have peat-filled depressions and sand rims. Two shell beds are present along the banks of the canal except in the central portion of the cross section of these two bays. Nowhere else in the area has solution of the shell beds occurred, although the Canal cuts across other peat-filled depressions without sand rims. It would seem, therefore, that the forces causing the bays are also connected with the loss of the shell beds either through furnishing drainage for solution or otherwise disposing of them (Figs. 23, 24).

14. Advocates of the solution theory maintain that the magnetic spot highs, which seem to be associated with most of the bays, can be readily explained by the redeposition, to the southeast of the bay, of the iron dissolved out of the bay by underground waters. If such action has taken place, two facts stand out, first, that such underground water movement would tend to destroy the southeast rim by undermining action, and, second, the iron would, if deposited, be relatively near the surface and in an elongated deposit running with the long axis of the bay. Such a deposit could not possibly give a spot high of the character observed in connection with these bays, but only a narrow northwest-southeast trending high magnetic ridge, not yet found associated with any single bay in the bay country.

15. If bays were formed by solution or artesian spring action, they would start as shallow depressions and the peat formed in them would be made up of marsh community or shrub-bog community plants; instead, in Jerome Bay and in Jones Lake Bay, Bladen County, Buell (1945) has found an aquatic plant peat filling which rests on a thick silt layer rather than directly on the sand. This evidence points to the presence of a deep-water lake before the beginning of sedimentation (Fig. 9).

Artesian Ground-Water Theory

Douglas Johnson (1942) has emphasized the fact, originally pointed out by Prouty (1934b), that bays in the northeastern part of the "bay country" have elongation to the east of southeast, while those in the southwestern part of the "bay country" have elongation more to the south of southeast. He explained this by: "... action of artesian springs, migrating in an up-dip direction, modified by the relative volume and direction of flow of the associated underground water." If these forces have the same direction, the direction of elongation of any bay at different periods of formation will be uniform and only the ellipticity will change; if the direction of the forces is different, the elongation direction as well as amount would vary with the relative strength of the two forces.

This theory assumes the formation of the bays on the more recently emerged and undissected marine terraces. As water rises near the center of the potential bay area, the weight of the sand above it is reduced, allowing a shallow depression to form by slumping of the sand toward the spring area. This peripheral slumping continues as the finer particles formed by the constant milling of the sand by the spring are carried away by the escape water, along with soluble materials. According to the artesian theory, all bays must have been lake basins in their early development stage.

Facts Against Artesian Ground-Water Theory

1. Johnson's (1942, p. 233–234) assumption of a practically undissected coastal plain at the time of bay formation is seemingly untenable. Slow uplift allowed streams to considerably dissect each terrace by the time the terrace had risen a few feet above sea level. Thus each lower terrace extends along the stream course, well up into the territory of the next higher terrace. Bays also occur on valley slopes and older flood-plain area.

2. According to this and other theories involving terrestrial forces, bay formation should have begun in early Glacial or late Pliocene time along the inner edge of the Coastal Plain and should be going on now in the lowest Pleistocene terrace area. We know of no such bays being formed now and there is no such age difference between the bays in the inner and the outer portion of the Coastal Plain.

3. Hydraulic and ground-water springs would tend to be more numerous along the foot of terrace escarpments, and therefore generally aligned in rows parallel to the coast. However, the most striking alignments are nearly at right angles to the coast line. In the lake country of southeast North Carolina there is a northwest-southeast grouping of a great number of relatively large bays. This grouping can be seen best in Plate 1, which is an accurate small scale map of all the larger and medium-sized bays shown on the aerial photographs of the bay country. This grouping is best explained by the meteoritic theory of bay origin.

4. If artesian springs originate along joints, depressions formed by the springs would tend to be aligned in the direction of the joints, as are numerous sinks near Sarasota, Florida (Pl. 19); or, if along more porous beds, they would tend to be aligned and elongated parallel to the strike of such beds. The alignment of bays can better be explained by the slightly different time of infall of meteorites and the simultaneous turning of the earth on its axis from west to east, at the rate of about 1250 feet per second average for the bay area. Though there is a strong tendency, particularly in the central part of the bay country, for overlapping of aligned bays to occur with the successively younger bays more and more to the northwest of the first bay formed in the group, alignment of the bays could possibly occur in any direction, because of the variable positions and times of fall of the different bodies in the supposed comet mass. Some alignments of bays are north-south, others are southwest-northeast.

5. According to the artesian spring theory (Johnson, 1942, p. 174–193), bay orientation is controlled by the tendency of the postulated artesian springs to migrate up dip, modified by the flow direction of local ground waters. The orientation of bays is entirely out of harmony with this theory for large sections of the bay area, even if one assumed a general movement of ground water toward the coast on an undissected sloping plane. For example, in the Norfolk area, the rock dip is nearly east

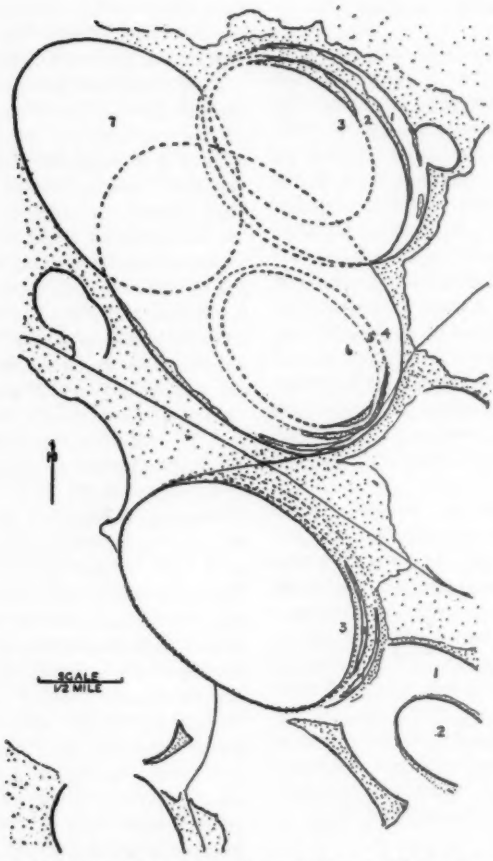


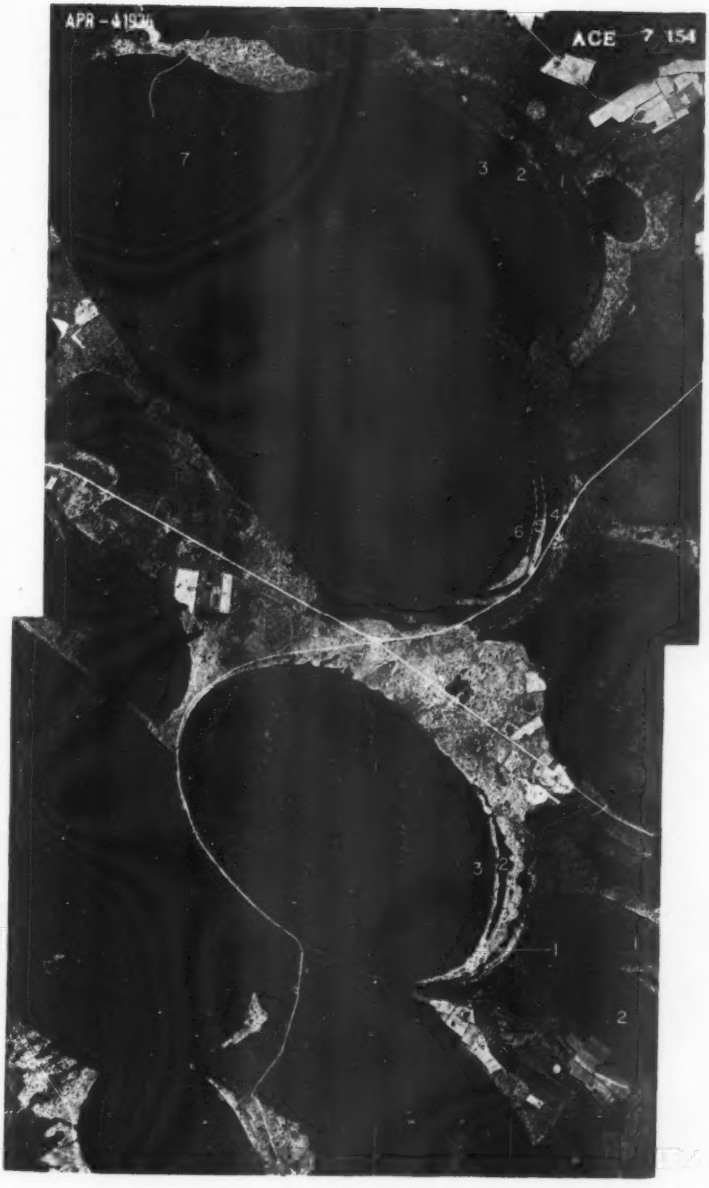
FIGURE 16.—MULTIPLE BAYS IN BLADEN COUNTY, NORTH CAROLINA

The bay toward the north, occupying an area of about 4½ square miles, has apparently been formed by overlapping of six or seven fairly large bays and one small bay. The lobate offset toward the northeast is formed by three separate bays of slightly different size and orientation, each longer than a mile. Northwest end of the big multiple bay was apparently formed by a large bay a little less than 2 miles long; southeast end was apparently formed by two bays, the larger one, over 2 miles long, making the outer rim and the smaller one with smaller curve making the inner rim.

A large and nearly perfectly elliptical multiple bay (lower center on Pl. 16) has an area of about 1½ square miles. The three rims at the southeast end are explained by the formation of three bays of about the same size, each a little west of the previous one. The east side of this bay was formed in sandy higher ground. The southwest side was formed in a deep swamp, where the sand was covered with water. The only logical way for a sand rim such as that occupied by the road to be formed is by some force pushing the sand from the depressed area under the bay. It could not have been built up by slumping of low ground toward the center of the bay, as required by both the artesian spring theory and the solution theory; nor could a sand rim be thrown up as a beach ridge by the wind where there is no beach and only swamp.

Practically the entire surface of this local area is occupied by bays. One of the more interesting types of multiple bay is to be seen just north of the southeast corner. Only a little over a half of it is seen, but it is clearly made up of two bays. The smaller is about half the diameter of the larger one and almost exactly in the center of the larger bay. It must have been formed later than the larger bay and have had its rim built up from bottom sand which was considerably below the level of present bay surface. Neither slumping nor wind action could do this.

Suggested order of formation of separate bays is shown by numbers.



MULTIPLE BAYS IN BLADEN COUNTY, NORTH CAROLINA
See Figure 16 for descriptive drawing.

BAYS ALONG THE INLAND WATERWAY, 8 MILES NORTHEAST OF MYRTLE BEACH, SOUTH CAROLINA

See Figure 17 for explanation.

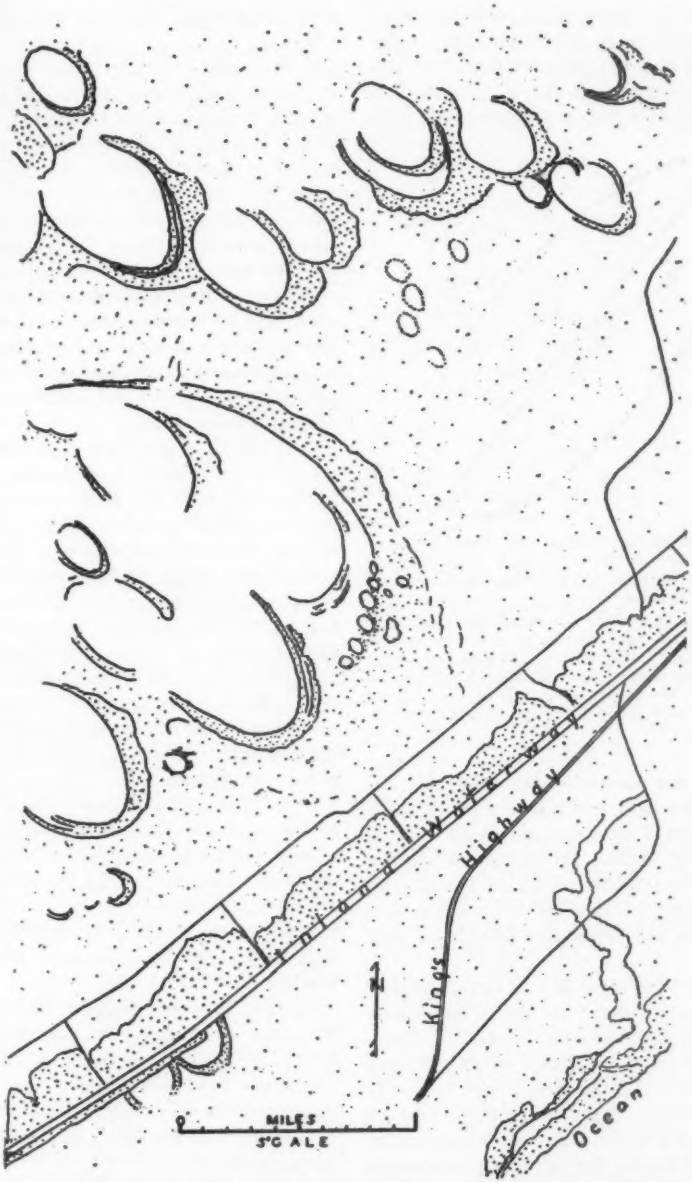


FIGURE 17.—BAYS ALONG THE INLAND WATERWAY, 8 MILES NORTHEAST OF MYRTLE BEACH, SOUTH CAROLINA

Ocean Lake Bay, the large multiple bay in left center, seems to occupy somewhat lower ground than the better-rimmed bays in the upper part of picture, and shows the effects of an inundation.

In lower left, along the canal, can be seen the southeast part of two small bays, one largely concealed, sectioned by the canal.

and the surface slope is nearly north. According to the artesian theory, this should give a northeast elongation of the bays, but bays here have southeast elongation. In the Wilmington Arch area, North Carolina, the surface beds slope

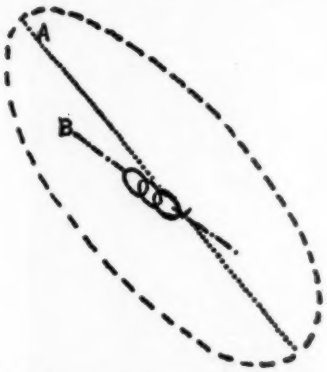


FIGURE 18.—RELATIONSHIP OF THE AVERAGE ELONGATION OF BAYS TO THE LINEATION IN PARTS OF BLADEN AND CUMBERLAND COUNTIES, NORTH CAROLINA

Shows the axis of the elongated area containing numerous large bays in Bladen and Cumberland counties (line A). This direction is also that of the elongation of most of the unit bays. The lineation direction of the overlapping bays in most of the multiple bays in this area of large bays is shown by line B.

southeast but the underlying older beds, involved in the arch, which govern the direction of movement of artesian waters, vary as much as 70° to 80° in their dip direction on the two sides of the arch. According to the artesian spring theory, this should give a much greater variation in bay orientation than is the case (Fig. 25).

6. Some bays occur in low elevations near streams; others occur in higher interstream areas. Both have the same direction of elongation, although the direction of ground-water movement in the two areas may be nearly at right angles. Again, bays that occur on opposite sides of the same valley have similar orientation despite the fact that ground-water movement in the two positions may differ by as much as 80° to 90°.

7. If bays were formed largely by artesian springs, we would expect to find the larger bays in lower ground where hydrostatic head would be greater, but there is no such conformity.

8. In Bladen County, as in other large areas, we find in many places from a third to a half or more of the ground area covered by bays. One is justified in questioning the source of such vast outflows of artesian water, especially when these bays are concentrated in a strip extending up-dip, where there would be a maximum competition by the bay-springs for the same water. The bays toward the southeast end in such a situation should have less artesian water and be less numerous and smaller, but this is not the case. If such a vast flow of artesian water is granted, we find it even more difficult to account for the relative absence of drainage erosion effects.

9. If the bays and their sand rims result from artesian springs and wind action, why do we have such high rims to the southeast when the most effective wind direction is known to be from the southwest and when the underground and surface drainage from bays, assumed by the artesian theory, is also supposed to be toward the southeast? If it is drained by surface run-off, a stream channel should develop; if it is by underground drainage, according to the multiple theory of Johnson, solution should cause slumping and prevention of the formation of a rim, or should breach any rim already formed.

10. If the Carolina Bays were formed by the artesian spring method, it is very difficult to believe that the structure and stratigraphy of the coastal plain rocks, which in the Cretaceous are known to be very lensy, would not be reflected in the location and lineation of the bays of that area. We do not know of any such relationship.

11. If all bays were originally artesian spring lakes, one would expect the most active lake-bottom springs to be in the near-coastal area, where the bays, according to the artesian theory, were most recently formed. Few, if any, bays of this type are known in the late terrace and near-coast areas.

12. According to Johnson, most, if not all, bay-lake-bottom springs occur toward the southeast end of the bays. This is where one would expect to find springs produced by meteoritic action. If the bays were lengthened

through up-slope migration of the artesian springs, it would seem reasonable that a substantial percentage of such springs should still be found toward the northwest end of the bays. As the land becomes more dissected, the ground water table is lowered and the effect of groundwater flow should be less potent in deflecting the flow of artesian waters; so that if artesian springs tend to work up-slope this tendency would be less opposed by groundwater as time went on and the spring should therefore be near the northwest end of the bay rather than the southeast.

13. Many bays have smaller rimmed bays entirely inside the area of their rims. It is not probable that, after a large bay had been formed by a large artesian spring, a small spring would develop in the bay lake area and build up a rim similar in shape and orientation to that of the big bay in which it occurs, above the level of the lake water. This is opposed to the artesian theory of bay formation through lateral slumping of the ground toward the spring and the building up of the rim by wind action on the beach sand. In this case, there is no beach. The same argument applies to the east rim of multiple bays which stand above the general level of lake water or swamp. Many bays are formed partly on high ground and partly on low ground. Obviously, artesian springs could not cause symmetrical slumping under such conditions.

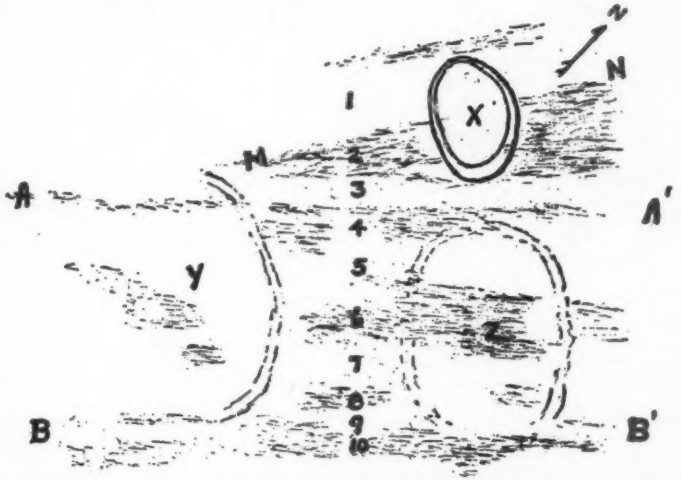


FIGURE 19.—INTERPRETATION OF POSITION OF BEACHES AND SWALES, 7 MILES NORTHWEST OF MYRTLE BEACH, SOUTH CAROLINA

(See Johnson, 1942). X, Y, Z represent bays. M–N, A–A′, B–B′ are ancient shore lines named in order of decreasing age. Odd numbers represent ancient beach ridges; higher numbers represent younger age. Some with higher numbers rather poorly developed. M–N is older than bay X. Even numbers represent swales between beach ridges younger toward the southeast. Bays X and Y are well preserved northwest of shore line A–A′. Bays Y and Z are poorly preserved between shore lines A–A′ and B–B′. Bay Z is completely destroyed southeast of line B–B′.

14. The same general rock and underground water conditions as are found in Georgia continue to the southwest in Alabama and in the Florida peninsula, yet bays are not found in these regions. Similar conditions exist to the northeast of the bay country and in areas where bays are sparsely distributed. Florida has but recently emerged from the sea, geologically speaking. There are many so-called "new land lakes", but there are no regular, elliptical, oriented, sand-rimmed depressions similar to bays except in the northeast corner of the State. The lake basins to be found to the east of Sarasota, for example, are roughly elongated with the joint system which controls their position, as one would expect, but their shape

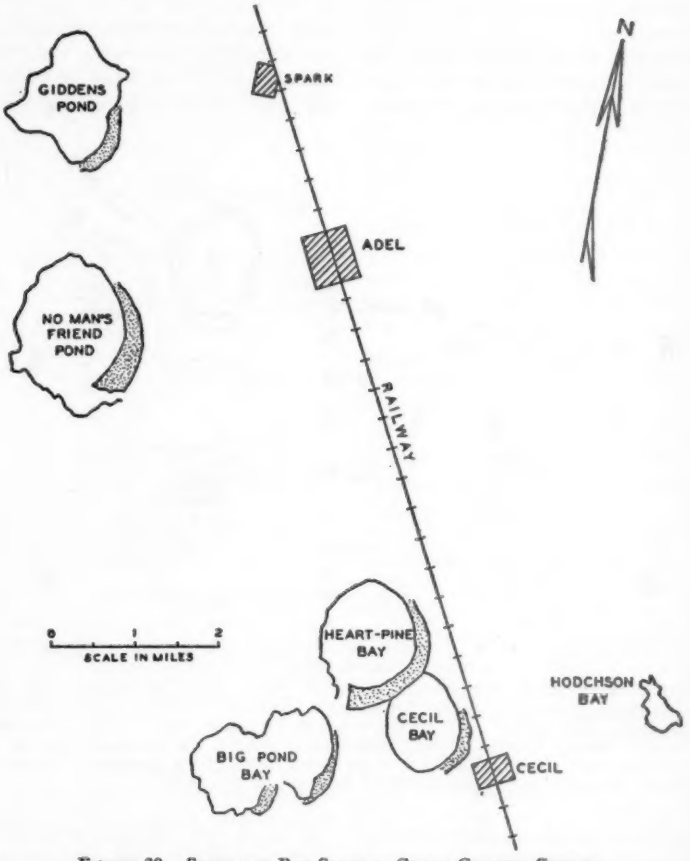


FIGURE 20.—SINKS AND BAY SINKS IN COOKE COUNTY, GEORGIA

The so-called Hodchson Bay in the southeastern part of the figure is a typical sink as it has no sand rim and no suggestion of ever having been elliptical. The five other so-called bays and ponds should be classed as "Carolina Bays." Each gives evidence of a well developed sand rim, in some cases now largely destroyed, and each shows evidence of former elliptical shape. The bays here shown are in a limestone country and are gradually changing into limestone sinks. Big Pond Bay was originally two contiguous bays. Solution has largely removed the rim between them. Giddens Pond, as suggested by a remnant sand rim to the southeast, is now more than twice its original size. Enlargement has been toward northeast, north, and west.

Direction of drainage and extension by solution in these different bays is very dissimilar, reflecting local drainage condition and not that of artesian water movement or deep ground-water movement. The soil survey map of Cooke County, Georgia, from which this overlay was taken was made before the "Carolina Bays" were well known and only the conspicuous sand rims were noted.

is extremely irregular. They have no sand rims, and their elongation does not correspond to the direction of dip or direction of near-surface underground water movement.

15. The geographical limitations are not explained by the artesian water theory nor by any other than the meteoritic theory.

16. If the artesian-ground water theory of bay formation is assumed, in areas where the direction of the two forces is different the bays would be either sinusoidal or crescentic, not elliptical (Fig. 26).

17. It is not possible to explain the heart-shaped bays which have down-slope conver-

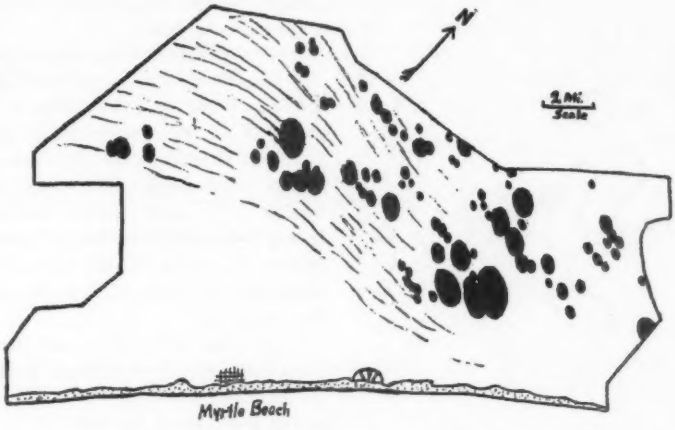


FIGURE 21.—RELATION OF BAYS TO PRESENT COAST LINE AND OLDER BEACH RIDGES OF MYRTLE BEACH

Sketch map showing the bays larger than 1000 feet long drawn to scale and their relationship to the present coast line with its broad beach dune area and to the older beach ridges, indicated here as fine lines. No bays are to be seen between the older beach ridges and the present beach although there is a distance of about 7 miles across this area to the northwest of Myrtle Beach. The two western bays which lap over the old beach ridge zone have had that portion which extends south beyond the beach ridges largely destroyed by erosion. It appears that the southern limit of the beach ridges marks the shore line at the time of the formation of the bays, or it marks the northern limit of a later-encroaching sea. *See* section on Age of Bays. (From aerial photograph mosaic of Myrtle Beach Estates. Inc., Horry County, South Carolina.)

gence of the long axes of their unit bays by the artesian theory (Fig. 26).[5]

Shoals of Fish Theory

Chapman Grant (1945) based an explanation of the Carolina Bays on the activities of "shoals of fish" at time of spawning. The shape of the bays (beds) developed supposedly depend upon the species or subspecies of fish; the size upon the size of the shoal; and the direction of orientation upon the direction of the prevailing wind, tides, currents, and flow of the fresh water from the submarine artesian

[5] Application of the artesian ground-water theory to some of the figures cited by Douglas Johnson (1942) follows:

1. Figure 34 of Johnson (1942): The bay toward the east must have been formed when ground water was more forceful than the artesian water because its long axis is nearly southeast, while the newer bay must have been formed when artesian waters had more force; but, according to the Johnson artesian ground-water theory, the bay on the west must have been formed during active up-slope migration of artesian water, and the older bay on the east must have been formed by the downward migration of the artesian spring controlled by the stronger ground-water flow. Since the western of the two bays is the younger, the theory does not fit the facts.

2. Figure 36 (Johnson, 1942, p. 184): All five compound bays show a westward migration for the successively younger bays. None shows an up-slope migration in either artesian or ground-water flow direction. Johnson noted this but did not recognize the implication, which is an argument against his own theory.

3. In the Myrtle Beach Area, where, according to Johnson, artesian and ground-water forces are about parallel, the bay in Johnson's Figure 5, with compound rims on the east side, shows that each of the successively younger bays was formed directly west of its predecessor. This also is not explained through the artesian theory but it, as are the others in the area and farther southwest in South Carolina and Georgia, well explained by the infall of a chain of meteorites on an eastward-turning earth with a tendency for the later infalls to be slightly deflected in their direction of fall.

4. It is also apparent from the above figure that the groundward drainage in Watts Bay was toward the northeast, where the rim has been breached, and not by way of the little bay to the southeast which, under Johnson's theory, would presumably be due in part to ground-water flow into it from the direction of Watts Bay. Instead of being breached here, the rim has actually been pushed slightly back into the big bay. This latter phenomenon can be seen in many overlapping bays and indicates a force such as a wind-shock wave, coming from the concave side of such rims. (*See* the rim in the small bay opening into the northwest end of Salter's Lake Bay, Pl. 4, fig. 2.)

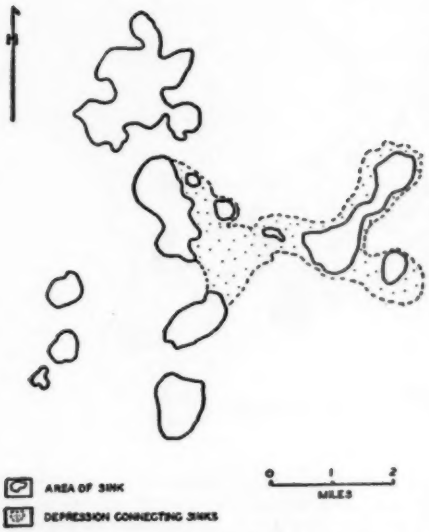


FIGURE 22.—LIMESTONE SINKS IN BAKER COUNTY, FLORIDA

Overlay of part of aerial mosaic no. 6 (Agricultural Adjustment Administration). Note absence of conformity of orientation of the typical limestone sinks.

springs which are the chief cause of the location of the spawning beds.

Some objections to this theory are:

1. No other areas of similar "beds" (bays) have been found and none are known to be in the process of formation anywhere in the world.

2. Cold water from the sub-oceanic, artesian springs would always tend to rise to the surface because of its lower density than sea water. It would not, therefore, flow oceanward at the bottom "to enable the fish to enjoy the fresh water while anchoring their bodies to the sandy floor of the bed."

3. Direction of incoming and outgoing currents differs greatly in different localities. This should give great difference in the orientation of the long axis of the bays.

4. It is difficult to understand how "heavy land wind" could cause the submerged fish to "face the wind" rather than the current.

5. The theory does not explain the sand rim at the northwest end of the bays.

6. According to this theory, the age of the bays would correspond to the age of the terraces on which they occur. The bays in different

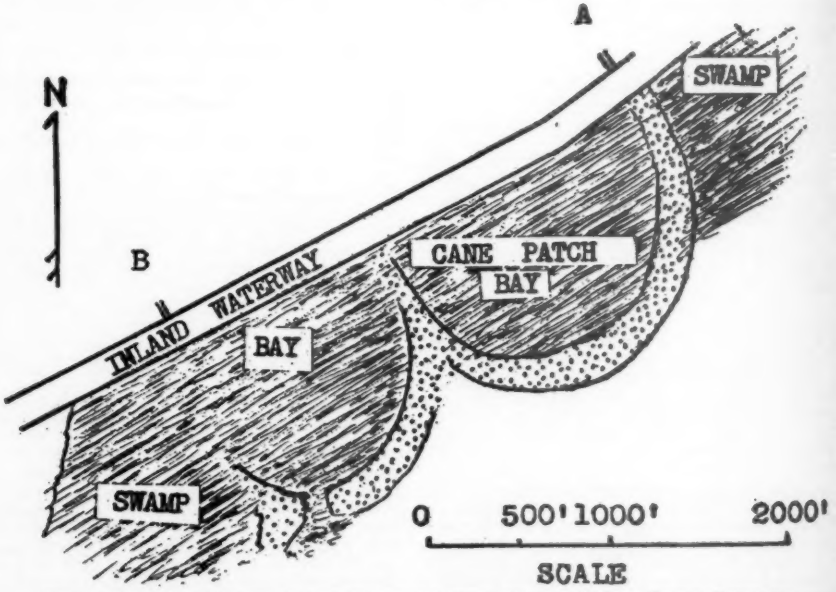


FIGURE 23.—BAYS CUT IN INLAND WATERWAY NEAR MYRTLE BEACH, SOUTH CAROLINA

See Figure 24 for cross section along line A–B.

parts of the Coastal Plain seem to be about the same age.

7. Some of the bays, up to 7 miles or more long, would seem to be rather large to be watered by a single artesian spring, and it also would seem to be too large an area to be successfully excavated by even a smoothly working and well disciplined shoal of fish.

bays of the entire Coastal Plain were developed during or prior to the formation of the well-known surfaces of marine planation" (Pleistocene terraces). This would mean that the bays were older than the terraces and any of the later marine beach ridges. The lack of fused glass, fragments of basement rock, and meteoritic material about the bays was explained by the length of time since their formation and the thorough weathering possible in that time. One bay surveyed toward the Fall Line seemed to show, by magnetometer tests, evidence of meteoritic material associated with the bay.

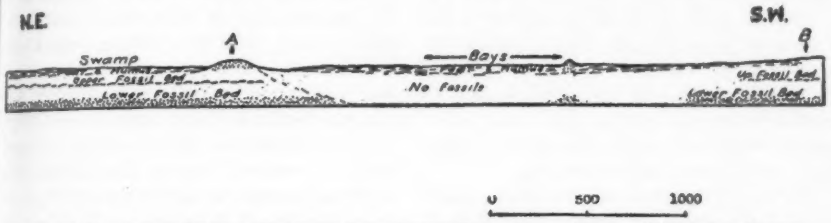


FIGURE 24.—CROSS SECTION THROUGH CANE PATCH BAYS, ALONG INLAND WATERWAY CANAL
For points on the cross section, see Figure 23. Vertical scale exaggerated.

METEORITIC THEORY AS ORIGINALLY PROPOSED

The revelation (Melton and Schriever, 1933; Melton, 1934b) that there existed a vast number of oriented, elliptical, sand-rimmed depressions, practically unrecognized before aerial photography made them apparent, startled the scientific world. That these depressions appeared to be of meteoritic rather than terrestrial origin aroused spirited scientific discussion and further investigation.

In the original paper by Melton and Schriever, the Carolina Bays were thought to have originated through the direct contact with the Earth of a vast number of meteoritic masses approaching the Earth from a general northwest direction and hitting the Earth at an angle of about 55° to the vertical. The general characteristics of the bays were described, their geographical distribution roughly determined as at least an area of 10,000 square miles, and the possible relationship of this area to that of the abundant meteorite finds to the northwest was suggested.

It was considered that the age of the bays is some time between Pliocene and late Pleistocene; that some of those shown in the photographs (between Conway and the coast line near Myrtle Beach) were covered by the sea at one time; and that: "It is probable that the

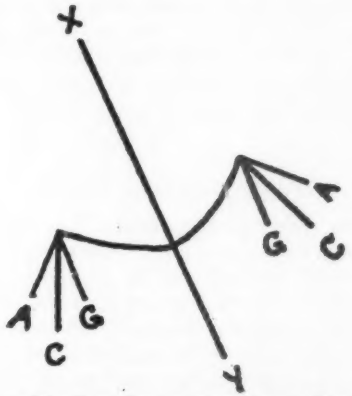


FIGURE 25.—DIRECTION OF ARTESIAN AND GROUND-WATER MOVEMENT IN THE WILMINGTON ARCH AREA, NORTH CAROLINA
A = Direction of artesian water force; G = Direction of ground-water force; C = Direction of combined forces.

The chief difference between the recorded Views of Melton and the writer is that the writer is convinced that the bays were formed in very late Pleistocene marine terrace time; that the depressions and rims were chiefly

formed by the air-shock waves accompanying the falling meteoritic bodies; and that the divergence in direction of elongation observed in different parts of the bay area is due to the general fanning out effect of the mass of meteorites as they passed through the atmosphere, in addition to the breaking up of many of the masses before reaching the Earth. The old-age appearance of the bays near the ocean is thought due either to their development in shallow water with partial destruction before marine withdrawal, or to subsequent inundation by temporary marine flooding.

The main criticism of the meteoritic theory as originally stated by Melton and Schriever (1933) is its inability to account for the great size of bays, their shallowness, and the lack of undisturbed strata beneath much area of each of the bays. These conditions are logically met only by the air-shock wave revision of the meteoritic theory, which finds its more recent example in the great Siberian meteorite of 1908.

Revised Meteoritic Theory

The writer (1934a; 1934b) has adhered strictly to the meteoritic theory since the outset of his study on the bays. He later (Prouty, 1935) suggested the probable important function of compressed air (air-shock waves) in the formation of the depressions and rims, and the possible function of the gas and steam explosions during meteorite penetration in the formation of the minor rims. This article also presented other new facts concerning the bays.

MacCarthy (1937) made a brief summary of bay characteristics and also commented briefly on numerous terrestrial theories of bay origin. Most of the article discussed the revised meteoritic theory and amplified the role of compressed air accompanying a falling body in the formation of the bay crater, suggested by Prouty (1935), and called attention to the Siberian meteorite, where (Whipple, 1930) five thousand times as much energy was dissipated in air compression waves (shock waves) as in seismic waves. He also discussed the experiments with high velocity rifle bullets shot, at different angles, into trays filled with clay covered with plaster of paris powder. The air-shock waves form large, shallow, rimmed depressions practically identical with bay craters. The elliptical bullet hole in the clay is small in comparison to the elliptical depression in the overlying powder.

Douglas Johnson (1942), in all the arguments used against the meteoritic theory, gave no consideration to the revised meteoritic theory, which holds that the depressions now known as Carolina Bays were formed not by direct splash and explosion of a meteorite hitting the hardrock Earth, such as at Meteor Crater, Arizona, but by the air-shock waves which in the sand cover of the Coastal Plain could readily make a shallow depression, many times the size of the splash crater. Many of his arguments against the meteoritic theory are therefore valueless when applied to the air-shock wave theory of origin.

Prouty (1943) presented evidence against the artesian and solution theories and arguments for the revised (air-shock wave) meteoritic theory. Attention was again called to the experiments with projectiles in forming shallow, rimmed, elliptical depressions, similar to bays.

Further discussion of the Revised Meteoritic Theory of bay origin is found in sections dealing with multiple and heart-shaped bays, ellipticity and orientation of bays, and the magnetometer surveys of bays.

Significance of Single, Multiple, and Heart-Shaped Bays

Two general types of Carolina Bays are recognized: the single bay type and the multiple bay type. The single bay type has one elliptical rim (Type 1, Pl. 5) or one elliptical rim and one or more crescentic, smaller, inner rims which are developed in the southern half or two thirds of the bay (Type 2, Pl. 6). Many irregular-shaped bays are made up of two or more overlapping single bays of either type 1 or 2. In some multiple bays, the direction of overlap is apparently random, but in others there is a distinct directional lineation. The direction of lineation is generally between west and northwest (Pl. 14, fig. 1). Lineated, overlapping bays give to the resultant multiple bay an elongation direction of less azimuth than that of the single component bays. Where the multiple bay is composed of two single

bays with the later one slightly smaller (the usual *size* occurrence) and to the west or northwest of the earlier bay (the usual *position* occurrence), the resulting multiple bay is usually heart-shaped with the sharper angle directed southeasterly (Pl. 15). This is due to both the relative positions of the earlier and later units in the multiple bay and to the counter-clockwise turning of the direction of elongation of the later-formed unit bay.

Douglas Johnson (1942) explains heart-shaped multiple bays, or as he expresses it "Bays of complex origin," as formed through variation in the direction and relative intensity of the two forces involved: (1) artesian water rising through the Coastal Plain sand cover and (2) ground water moving to lower level (down dip) through the same sand bed. Artesian springs, according to Johnson, move up slope either by erosion of the escape aperture, beneath the surface sand blanket, or by the much more important factor, a greater angle of upflow of the water from the aperture through the sand, caused by either increased hydrostatic pressure or volume increase relative to the ground-water flow. If the dip of the beds which carry the artesian water and from which it escapes is different from the direction of flow of the ground water through the sand in which the artesian water is rising, migration of the artesian spring will vary direction according to which of the two forces is the stronger. According to Johnson, such a spring will begin with little volume, grow strong with time as opening through aquifer cover is enlarged up dip, reach a maximum discharge volume, and then decrease slowly. An analysis of the forces postulated by Johnson shows the general shape of the resultant bay to be sigmoidal or peanut-shaped, rather than elliptical (Fig. 26). In no case could convergence of the axes of the two unit bays be in a down-slope direction. If the lines of force of artesian migration and ground-water runoff converge down slope, the multiple bay units will diverge down slope with the later-formed bay on the west. If the two forces converge up slope, the units bays will still diverge down slope but the later-formed bay will be on the east.

In applying the process of increase and decrease of artesian flow under conditions where the dip direction of artesian beds is different from the flow direction of the ground water, it is observed that the migration of the artesian spring is along a curved line as long as the force of the spring is changing relative to the force of the ground water. As long as the volume of the artesian water increases, the spring will migrate more and more toward the up-dip direction of the artesian bed. Its maximum artesian flow is reached at point 1 (diagram A, Fig. 26). As the artesian volume decreases and the up-dip migration becomes slower, the mi-

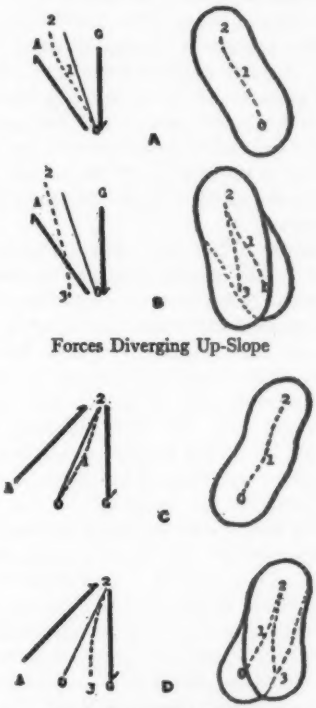


FIGURE 26.—VARYING CONDITIONS OF GROUND-WATER AND ARTESIAN FORCES

Showing anticipated results in bay formation under the Johnson (1942) theory. A = artesian force direction; G = ground-water force direction.

A>G A increases from 0 to 1 and decreases from 1 to 2. At 2, A equals G.

G>A A constantly decreases from 2 to 3.

A>G A increases from 0 to 1 and decreases from 1 to 2. At 2, A equals G.

G>A A constantly decreases from 2 to 3.

gration of the spring swings more and more toward the line of the ground-water run off (curve 1–2). At point 2, the spring ceases to migrate up dip because the force of the ground water, tending to cause migration in a general down-slope direction, is now equal to the force of the artesian spring water, tending to cause migration in a general up-slope direction. With further decrease in the artesian flow, relative to the ground-water flow, the spring begins to migrate in a general down-slope direction, following a curved line which tends to run more and more in the direction of the ground-water runoff as the artesian water volume gradually decreases.

According to the above theory, a single bay formed by the general up-slope migration of the artesian spring is shown in diagrams A and C. A complex bay would be formed by the migration of the artesian spring back down the general slope direction. Diagrams B and D show the combination of the two unit bays in the multiple bay. The bays (Johnson, 1942, Figs. 34, 36) do not conform to the shape of bays formed according to his theory.

The direction of elongation of the bays, resulting from the interaction of the two forces as postulated by the artesian ground-water theory, does not fit the facts in much of the bay territory. In the Norfolk, Virginia, area, according to the theory, the elongation should be northeast whereas in reality it is southeast. Again on the two sides of the Wilmington Arch, covering a large territory in North Carolina, the elongation direction is practically the same, but according to the artesian ground-water theory there should be a wide divergence. In many parts of the bay area, bays occurring on the opposite slopes of the same valley have similar elongation direction, although the movement of the ground water in the two positions may have a directional difference of as much as 90°.

We have already seen that the meteoritic theory of bay formation offers an explanation for the gradual change in the direction of elongation of the bays as observed along a northeast-southwest line. The meteoritic theory also seems to offer a reasonable explanation for the numerous heart-shaped bays through the infall of pairs of tandem meteorites. The trailing meteorite of the tandem would hit the east-turning Earth farther toward the west, because of its later arrival, and farther to the northwest, the direction from which the meteorites were falling, because of its smaller size and less moment of momentum. The counter-clockwise turn of the direction of elongation of the unit bay formed by the trailing or smaller meteorite is explained by the position of its path to the west of the axis of the air-shock-wave cone of the tandem meteorite which preceded it (Fig. 27) representing an oblique, north-looking, aerial view of a pair of tandem meteorites falling at an oblique angle to the Earth in the direction of the observer. It also shows the relative size and position of the shock-wave cone from meteorite A at different instants of its fall and the slightly converging paths of the two tandem meteorites A and B. The upper ellipse, A′ at its center, marks the location of a cross-section view of the shock-wave cone made by meteorite A, the first of the tandem pair of meteorites A and B, at the moment that A occupies the position A″. The first meteorite traveled along the axis of this cone, which is constantly enlarging at any one cross section and at the same time is being carried to the east by the turning of the Earth and its atmosphere, at an average rate of about 1250 feet per second at the Earth's surface in the latitude of the Carolina Bay Region. By the time the second meteorite of the tandem, B, arrives at a given cross section of the shock-wave cone of meteorite A, the cone has shifted so that the second meteorite B is not following the displaced path of the first meteorite A but travels a path to the west of it. B is therefore being constantly drawn eastward toward the greater vacuum area of the preceding pressure cone. The atmospheric paths of the two meteorites A and B, therefore, converge as they approach the Earth. Since B is forced to travel more and more with an easterly component as it falls, the azimuth of orientation of the bay formed by B is less than that formed by A. The resulting multiple bay is, therefore, heart-shaped with the point toward the south of southeast (Fig. 28).

Infall of tandem meteorites also explains lineated bays of both unit and multiple type where the tandem may consist of a larger number of tandem meteorites. Also random infall of

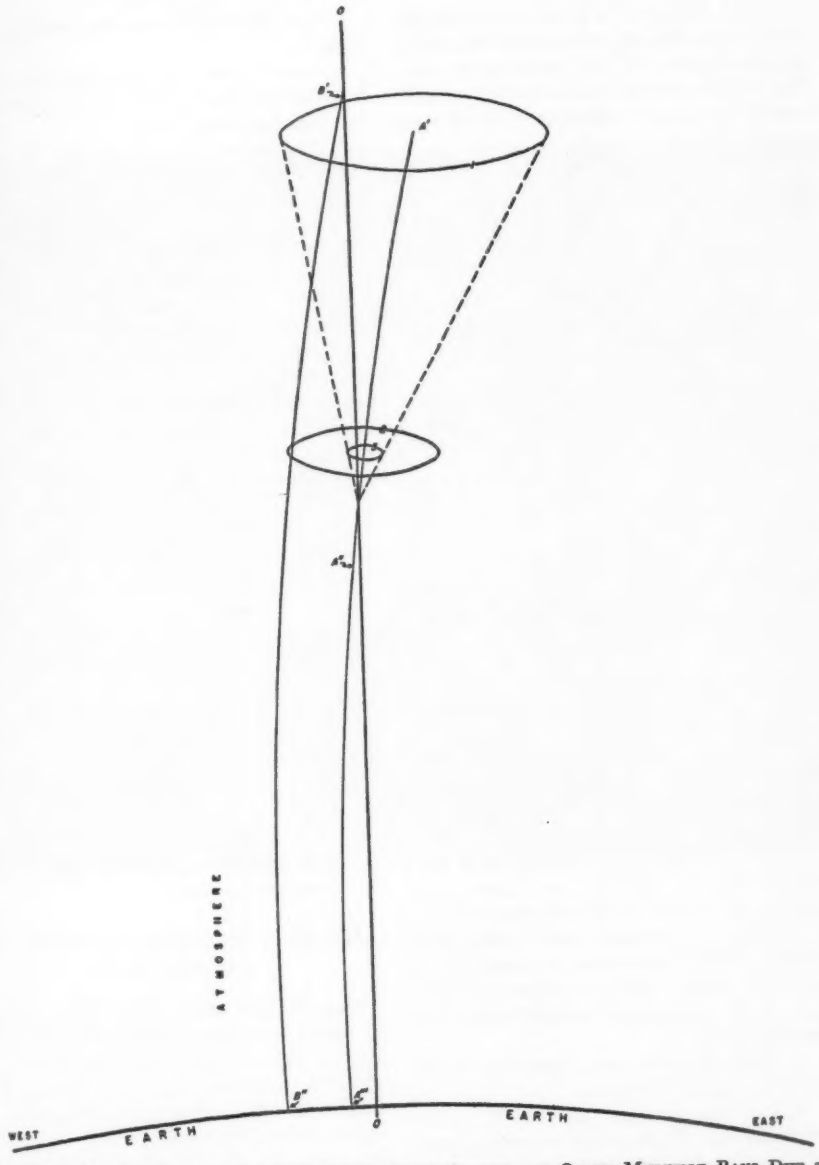


FIGURE 27.—FACTORS IN THE DEVELOPMENT OF HEART-SHAPED AND OTHER MULTIPLE BAYS DUE TO TANDEM METEORITES

See section on Significance of Single, Multiple, and Heart-Shaped Bays. Ellipse 1 is compression cone from meteorite A at the time of arrival of meteor B; ellipse 2 is compression cone from meteorite A when meteorite B arrives at this locality; ellipse 3 is compression cone from meteorite A when meteorite A is at point A″; A′–A‴ is the atmospheric path of meteorite A at moment it hits the earth; B′–B″ is the atmospheric path of meteorite B at moment it hits the earth; O–O is the direction of gravitational pull on both meteorites A and B.

meteorites may give the same type of multiple bay or even a divergence of the axial elongations opposite to that of the heart-shaped bays. This could be accomplished in several ways, for instance by change in direction of fall of some

FIGURE 28.—HEART-SHAPED MULTIPLE BAY FORMED BY IMPACT OF TANDEM METEORITES

Shows the "Multiple Bay" formed by the impact on the Earth's surface of tandem meteorites A and B (*see* Fig. 27). The different orientations of A and B give a heart-shaped "complex" or "multiple" bay.

meteorites due to coming apart or "exploding" as they near the Earth.

FACTS ANSWERED BY REVISED METEORITIC THEORY NOT ANSWERED BY TERRESTRIAL THEORIES

The revised meteoritic theory appears to explain a number of observed facts not satisfactorily answered by other theories:

1. Bays have limited geographical distribution throughout a vast area which offers equal opportunity to bay development under terrestrial theories of origin.

2. Carolina bays were formed in a very limited time. No such bays are known to be forming at present time, although the terrestrial forces of solution, wind action, earth rotation, artesian springs, etc., are undiminished and the Coastal Plain conditions in many parts of the world are as favorable now as they have ever been.

3 Some bays have been formed completely inside the rims of older bays.

4. The best developed bay rim is at the southeast end. Underground or surface water which escapes from the bay, according to either the artesian spring or solution theory, should lower this part of the rim by erosion or solution. The prevailing southwest winds tend to form the highest rim on the northeast side and not at the southeast end.

5. The bays have associated magnetic spot highs.

6. Area of most abundant meteorites found in the United States is just to the northwest of the "Carolina Bay" area.

7. The deepest part of the bays is toward the southeast end and to the west of the long axis of the bay. This position is to be expected, if formed by meteorites moving from the northwest and hitting the rotating Earth at a moderate angle to the horizontal.

8. Rock character, rock condition, and topography have no apparent effect upon the distribution or character of the bays in the Coastal Plain.

9. Bays maintain their direction of elongation in a given area despite changing direction of slope and drainage.

10. Many of the larger bays are made up of a number of overlapping bays. These "multiple bays" are formed by a few or many smaller bays of variable size and overlap. They may also have slightly different orientation, and there is no apparent rule to govern the order of formation or direction of overlap.

11. Large bays, 2–7 miles long, formed in areas of little or no calcareous rock are difficult to explain by solution, artesian springs, winds and currents, deflective force of earth rotation, or schools of fish theories.

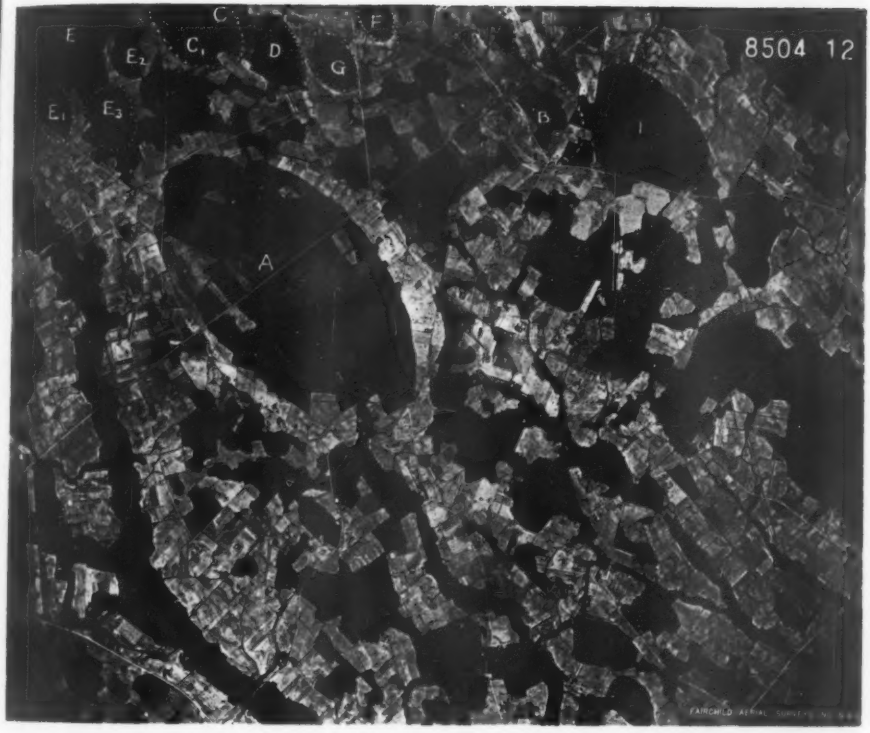
12. Most heart-shaped bays have southeast convergence of long axes.

13. The initial deposit in bays is a wind-blown silt overlain by peat which carries spores from deep-water plants.

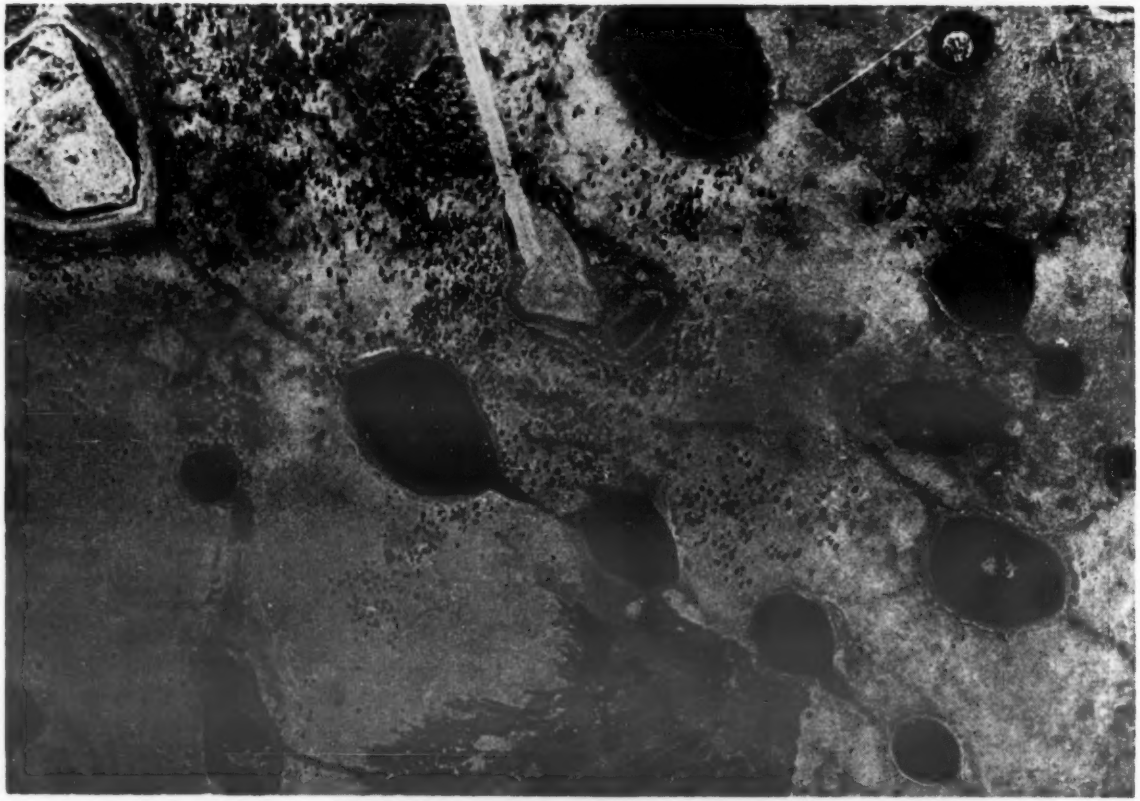
MAGNETOMETER SURVEYS AND ORIGIN OF CAROLINA BAYS[6]

Magnetometer surveys have been conducted by parties from the University of North Carolina at various times since the Summer of 1933. Two relatively large areas, Syracuse Bay Region, South Carolina (Pl. 18), about 14 square miles, and Sessom's Bay Region of Bladen County, North Carolina, about 20 square

[6] Editorial note: Professor Prouty energetically studied many of the Carolina bays with the magnetometer and at the time of his death had a sizeable manuscript illustrated with many local isogamic maps. At this place, his summary statement will suffice, together with six of his most interesting maps (Figs. 29–32, 34, 35).



SYRACUSE BAY AREA, SOUTH CAROLINA
See Figure 35 for magnetic-survey data.



LIMESTONE SINKS NEAR SARASOTA, FLORIDA

Developed along joint planes. Some have the shape of bays, but none have sand rims. The elongation and lineation are due to joint control.

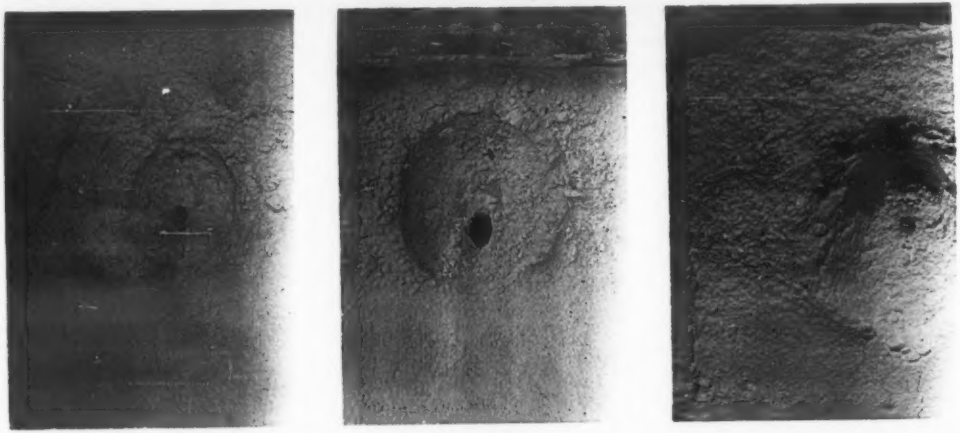


FIGURE 1

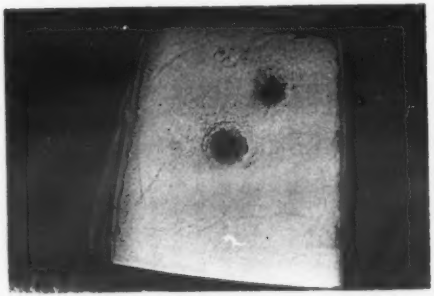
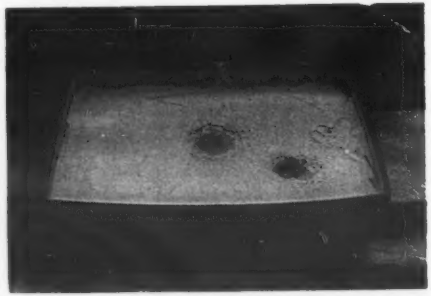


FIGURE 2



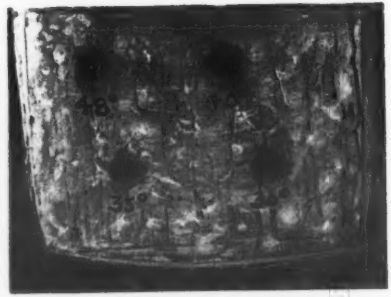


FIGURE 3

MODELS USED IN PROJECTILE EXPERIMENTS

miles, have been rather carefully surveyed, as have also the White Lake Bay Region with adjacent bays, 16 square miles, and the Dial

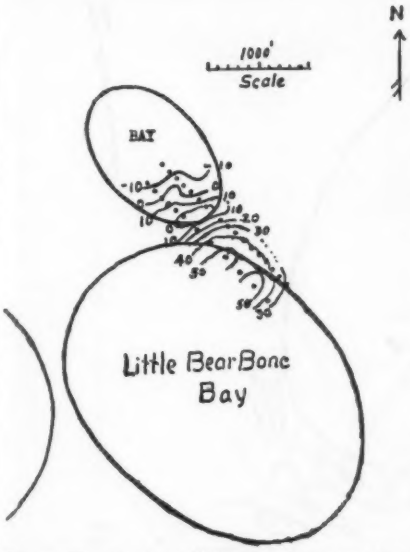


FIGURE 29.—ISOGAMIC MAP OF AREA IN AND SOUTHEAST OF SMALL BAY JUST NORTH OF LITTLE BEAR BONE BAY, MYRTLE BEACH ESTATES, SOUTH CAROLINA

In this reconnaissance survey, 31 readings (shown by dots) were made, showing a difference of 60 gamma. Two spot highs occur in positions essentially normal for the corresponding bay.

Bay group of bays in Florence County, South Carolina, 6 square miles.

In some portions of the Carolina Bay area, linear magnetic highs occur. These are thought to be caused by the presence (in the rock-floor of the Coastal Plain) of folded or tilted beds or tabular deposits of more highly magnetic nature than that of the average basement rock. These linear highs usually trend, with much local variation, in a general northeast-southwest direction. These linear highs complicate the readings of spot highs which occur on them, and necessitate the elimination of the linear high factor before the spot high can be correctly drawn. This elimination has been attempted through the utilization of carefully constructed convergence lines based on the magnetic readings in the area of the survey far enough away from the bays to be apparently unaffected by them.

It has been difficult to find a district for magnetometer survey which is sufficiently accessible and at the same time has bays which are widely enough spaced to give diagnostic readings for the individual bays and the interbay spaces. In most regions, large swamps make much of the territory unacceptable for accurate survey, because it is impossible to maintain a level instrument long enough to get accurate readings on the unstable swamp floors. Often, also, such swamps conceal small bays in the dense vegetation. Since such bays are not known to be present any spot highs originating from their presence would lead to false conclusions in regard to the relationship of spot highs to bays.

In all the surveys so far made with the magnetometer, no bay has failed to give indications of an associated spot magnetic high. All large bays so far surveyed, except one, have yielded large spot magnetic highs, and this

PLATE 20.—MODELS USED IN PROJECTILE EXPERIMENTS

FIGURE 1.—EFFECTS OF SHOOTING BULLETS INTO FINE POWDER OF DIFFERENT DEPTHS AND CONSISTENCY.

Angle in each case is 35° to horizontal; the bullets pass toward top of figures. Distance is 30 feet. In *A*, about $\frac{3}{16}$ inch plaster of paris covered the tray; in *B* about $\frac{3}{16}$ inch flour covered the tray; in *C* about $\frac{1}{8}$ inch of flour covered the tray. In each case the crater (made chiefly by the air-compression wave) is many times the size of aperture through the tray bottom. In deeper powder of same kind (compare *B* and *C*) aperture through tray is more toward front. In each case also aperture in tray bottom has greater ellipticity than crater in powder.

FIGURE 2.—RESULTS OF BULLETS FIRED FROM HIGH-POWERED RIFLE INTO PLASTICINE CLAY COVERED WITH PLASTER OF PARIS.

In *A*, bullet traveled toward top. In *B* projectile traveled toward the right.

FIGURE 3.—APERTURES MADE BY BULLETS PASSING THROUGH HORIZONTAL SHEET OF PLASTIC CLAY AT ANGLES OF 30°, 35°, 40°, AND 48°.

Photo is taken from directly above center of model. Shows effect of angle of impact on ellipticity.

exception yielded a spot high in the accustomed position but of much smaller size than usual. The general position of the associated magnetic highs is to the south of the southeast end of the bay. It may be due south, a little east of south, or a little west of south, depending upon conditions, but generally it is a little to the east of south. If the magnetic area is a single spot high, it is usually at a distance from the southeast end of the bay of about the length of the short axis of the bay rim. If the magnetic area is made up of more than one spot high, then each of these smaller units occurs at a relatively smaller distance from the bay, as explained elsewhere. Bays with increased ellipticity are generally a greater distance from their associated highs (Fig. 33).

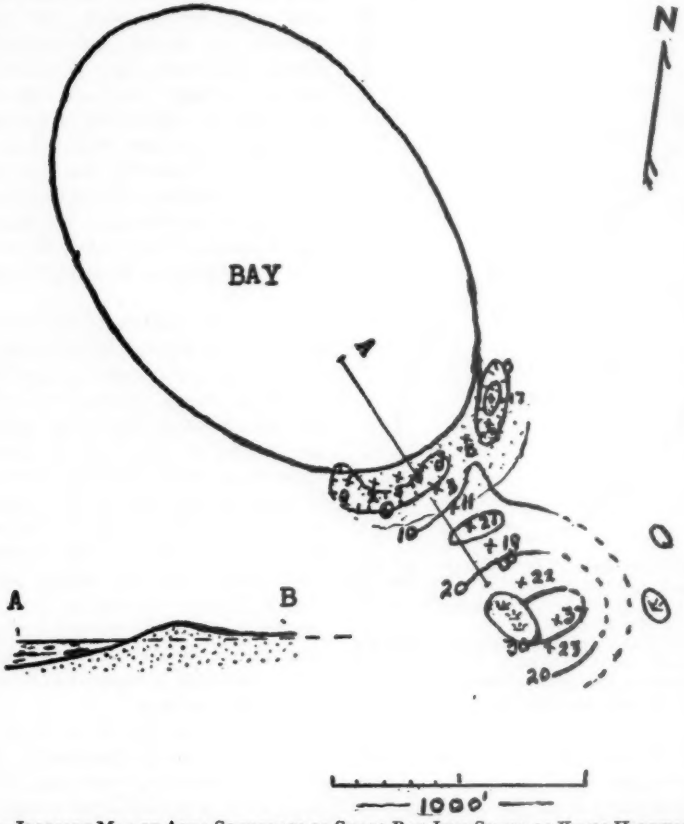


FIGURE 30.—ISOGAMIC MAP OF AREA SOUTHEAST OF SMALL BAY JUST SOUTH OF KINGS HIGHWAY, MYRTLE BEACH ESTATES, SOUTH CAROLINA

The extremes in the readings differ by 54 gamma. Two minor spot highs occur about 400 and 800 feet east of south from the southeast end of the bay. In cross section, A–B vertical is exaggerated 10 times.

The above so-called "Prouty Rule," named by Johnson (1942), was formulated in regard to bays with single associated highs. The original statement concerning the relative position of a magnetic spot high to the bay was never intended as a statement of exact relative position as the words "approximately" and "about" would indicate. The so-called rule generally applies in cases of bays with single spot high, but where there are two or more magnetic highs associated with the bays, the "rule" can-

not apply for previously stated reasons. Despite the publication of these facts (Prouty, 1934b; 1935; MacCarthy, 1937) and written communication concerning them, Johnson (1942) has thrown out the location statement, dignified by him a "rule," because it does not fit the bays with more than one associated magnetic high. It is possible that, after further study, the so-called rule of location of highs in respect to bays may not be found tenable, but it should be applied in accordance with specifications and published modifications.

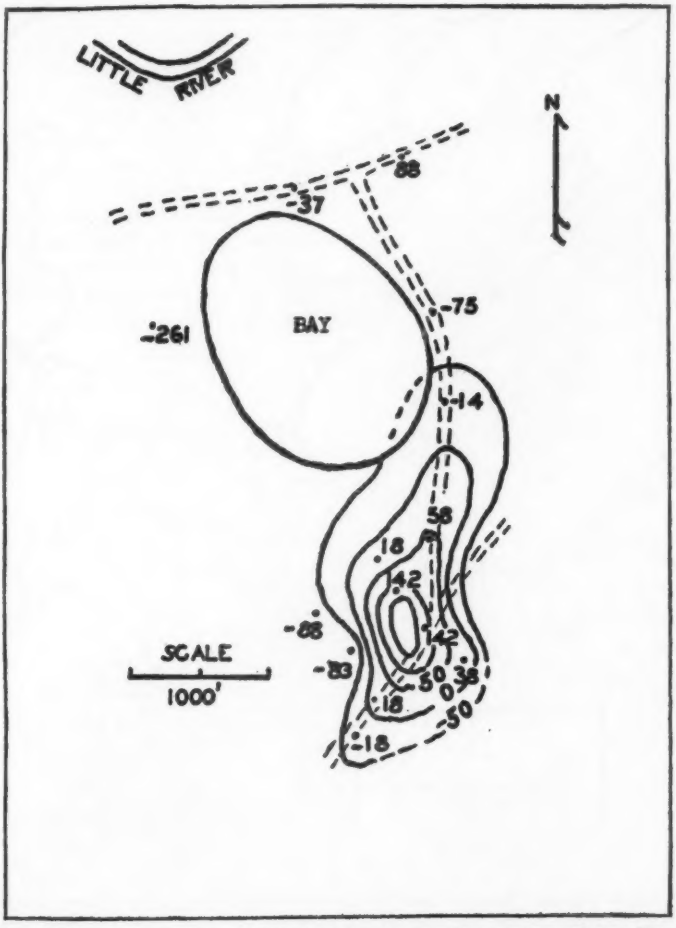


FIGURE 31.—ISOGAMIC MAP OF SMALL BAY IN NORTHEASTERN PART OF FORT BRAGG RESERVATION, NORTH CAROLINA

The spot high is over 400 gamma above the lowest magnetic reading. The position of the spot high would indicate the meteorite to occur in about a normal position relative to its corresponding bay.

The 88 gamma reading to the north is probably associated with a small bay largely hidden in the floodplain of Little River.

The interpretation of each spot magnetic high from the standpoint of the meteoritic theory is: The meteorite, in a single piece or perhaps in several pieces, hit the earth at an angle of about 35° to the horizontal, travelling from a general northwest direction. (Variation

FIGURE 32.—FINAL ISOGAMIC MAP OF THE WHITE LAKE-SINGLETARY LAKE, NORTH CAROLINA, AREA

The spot high indicated by the 700 isogamic line northwest of White Lake is thought associated with bay A. The double high north and northeast of White Lake is associated with bays B and C. The elongated distribution of the 400 and 500 isogams west of White Lake are attributed to the small bays 1, 2, 3, 4, and 5. The large spot high south of White Lake is associated with that bay, while the westward elongation of this high is attributed to bays 8, 9, and 10. The south extension of the high occurring directly west of Singletary Lake is thought caused by bays 11, 12, 13, and 14. The spot high of 200 gamma, east of south of Singletary Lake, is associated with that bay, while the small spot high of 111 gamma is likely associated with bay 18.

in direction of elongation of bays is explained elsewhere.) The portions of the meteorite not lost through vaporization by the heat of infall lie buried near the southeast end of the bay. The maximum magnetic line of force from such buried mass or areas of condensed meteoritic matter would crop out directly to the south, where a line rising at about 70° to the horizontal from the buried magnetic mass would reach the surface. The rotation of the earth

from west to east during the penetration of the meteorite would cause the magnetic body to be deflected slightly to the west of its normal course. Other factors causing deviation from the straight line penetration could be: (1) a non-spherical shape of the meteoritic mass, caused by the splitting of the meteorite in its passage through the air; (2) the rotation of the mass; or (3) the character or attitude of the rocks penetrated. Some deflection should be expected and the direction of deflection should also vary. If the meteoritic mass split into two or more pieces before contact with the earth, the position of each small piece may be some distance from the others. Thus we may have more than one high point in the so-called spot high. Each separate unit of the meteoritic

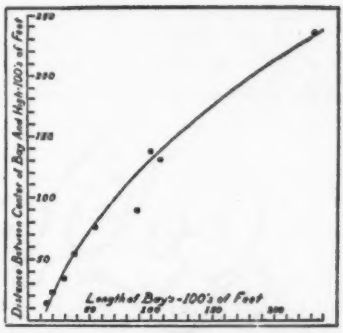


FIGURE 33.—RELATION BETWEEN LENGTH OF MAJOR AXES OF NINE TYPICAL BAYS AND DISTANCE FROM CENTER OF EACH BAY TO CENTER OF ASSOCIATED HIGH

(After MacCarthy, 1937).

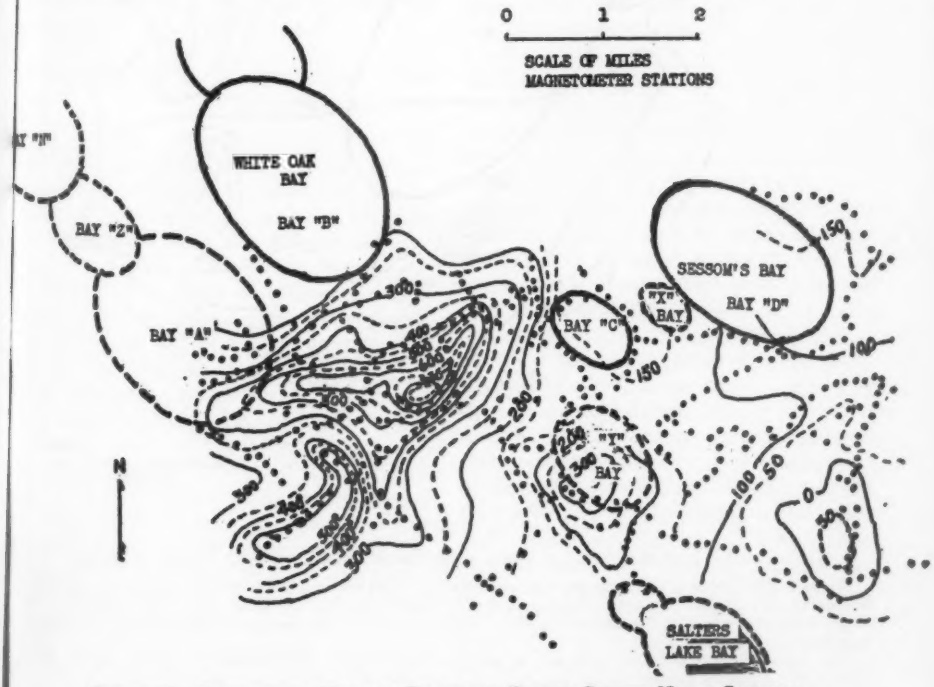


FIGURE 34.—GEOMAGNETIC MAP OF A PORTION OF BLADEN COUNTY, NORTH CAROLINA

After McCampbell (1945) modified by writer to show additional bays (dashed outlines). Dots represent the 366 magnetometer stations. The magnetic spot high (500 gamma) southeast of bay "A" is believed to be the meteoritic mass that formed that bay. The elongated high southeast of White Oak Bay ("B") implies one large and several small meteoritic masses associated with White Oak Bay and the adjoining one to the north. The magnetic high (300 gamma) in the approximate position of bay "Y" is likely associated with bay "C" to the north. The fourth spot high, in southeast corner, has the proper distance and position to be associated with Sessom's Bay ("D"). Note closer proximity of the multiple high to bays "A" and "B" than the single spot highs to bays "C" and "D".

mass would penetrate the earth to less depth than would the several units combined in a single mass, so that each of the minor or unit spot highs would appear closer to the southeast

can be accounted for by: (1) difference in the composition of the meteoritic masses making the different bays (the meteorite may be either stony or metallic); (2) the relative amount of

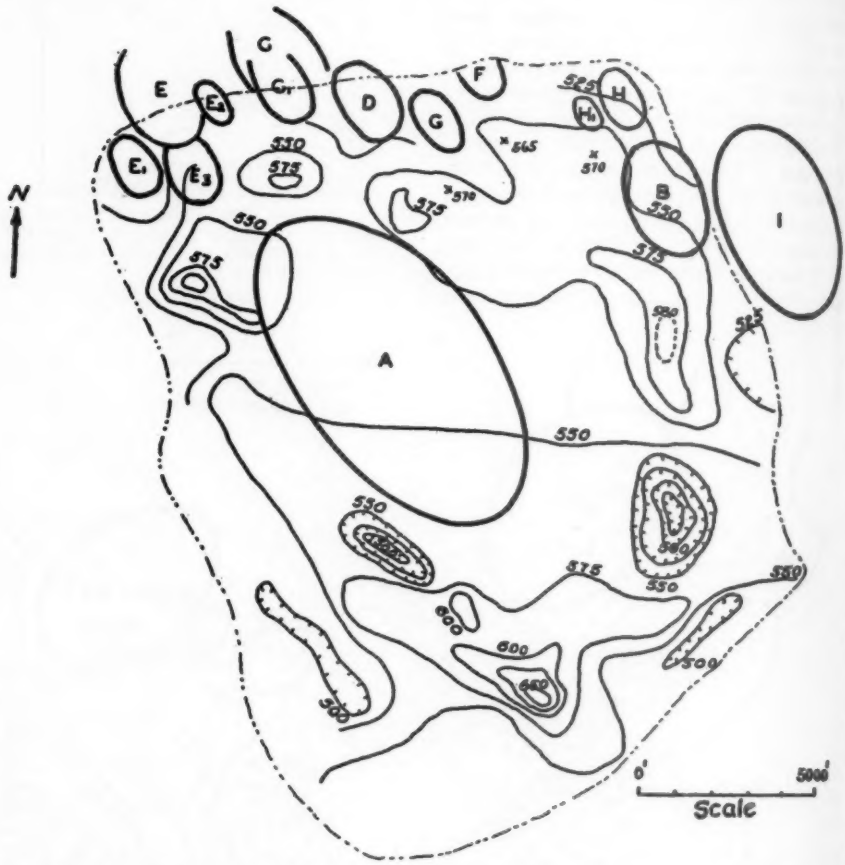


FIGURE 35.—ISOGAMIC MAP OF AREA SURROUNDING SYRACUSE BAY, SOUTH CAROLINA

An east-west linear high in the crystalline basement rocks was compensated for to give the magnetic anomalies used in this final map. Syracuse Bay "A" shows two spot highs implying two meteorites. The larger meteorite (showing the highest anomaly) penetrated the sediments farther, giving the more distant spot high.

Spot highs for bays B, D, E, F, G, and H show normal positions, but the one for bay C is slightly more west of south than is normal.

end of the bay than would the spot high formed by the penetration of the entire mass in one body. Many bays have minor spot highs in the associated magnetic-high area.

Difference in the magnitude of spot highs associated with bays of about the same size

volatilization during emplacement, because of difference in water content or in rock character; (3) the relative amount or character of chemical alteration since emplacement. The chemical changes would depend upon many factors such as: (1) size of the meteoritic masses, whether in

large chunks or in fine condensation particles; (2) the chemical nature of the underground waters and their rapidity of circulation.

With the possibility of such variable conditions, one should not be surprised at relatively large differences either in the position of associated magnetic highs or in their relative size. The main evidence is that there exists a high magnetic area associated with the southeast end of the bays and that there is no such relationship to other parts of the bays, nor, up to the present, have such spot highs been observed in the Coastal Plain areas clearly unassociated with bays, although it would not be unreasonable to expect such spot highs to be associated with mineral deposits or basic igneous rock plugs in the crystalline rock floor of the Coastal Plain. The larger bays as a rule have larger associated spot highs.

Experiments With Projectiles Shot Into Stratified Materials

By shooting bullets at an angle of 30° and 35° to the horizontal into a tray containing a lower layer of a different consistency from that above, it is possible to demonstrate the effect of the air-shock waves on the upper and more readily moved layer and the different effect of the projectile on the lower and more resistant layer. When the upper layer is thin, the projectile and the air-shock waves make a relatively large, elliptical, shallow-rimmed depression and the projectile makes a relatively small, elliptical-rimmed depression a little back from the center of the larger elliptical area formed by the air-shock waves. The projectile hole is farther forward when the upper layer is thicker. When plaster of paris powder or flour is spread over the bottom of a tray, the combined projectile and air-shock waves form an elliptical-rimmed depression in the powder and the projectile alone has sufficient force to form a small elliptical aperture in the bottom of the tray (Pl. 20, figs. 1, 2, 3). The same general effect is gained by having a layer of plastic material such as plasticine spread over the bottom of the tray and a layer of plaster of paris above it. When the projectile is shot into this from a distance of about 30 feet, the aperture in the plasticine layer is slightly larger than in the bottom of the tray and a high elliptical rim is formed about the projectile, with the highest part of the rim toward the front. In this case, it is more difficult to get the full applied force of the air-shock waves toward the front of the ellipse, because of the interference of the high rim formed by the plasticine in front of its ellipse.

It is noted that the rimmed elliptical depression made by the projectile and air-shock waves in the light powder (Pl. 20, fig. 1) is always less elliptical than the aperture made in tray bottom or in the plasticine. This would seem to indicate a smaller angle of infall of the meteorites than that previously assumed (35° to the horizontal) for the revised meteoritic theory.

The conditions in the Coastal Plain Area seem ideal for the formation of the elliptical, rimmed depressions (Carolina Bays) by the infall of meteorites at an angle of between 30° and 35° to the horizontal. There is in general a sandy blanket, some 10 to 20 feet or so thick covering the slightly more resistant, older Coastal Plain formation. The air-shock waves associated with the meteorites in their passage through the atmosphere into the Earth would tend to remove a large amount of the near-surface sand and less of the deeper deposits. The finer sand would tend to be carried a greater distance from the point of contact than the coarser sand particles. The projectile would enter the Coastal Plain considerably back of the center of the surface ellipse (Pl. 20, fig. 1) but, as it penetrated farther into the earth, the deepest place in the finished depression would be moved considerable toward the front. Since in the Coastal Plain the water table is usually only a few feet below the surface and the material is sandy, any depression would tend to be filled by the settling of the water-soaked sand until an angle of rest in that particular layer was attained. This explains the general shallow character of the bays and also in part the terraced condition of their cross section. In the process of formation, there might be instants of greater explosion caused by a penetration of the more resistant layers. These minor explosions could also explain some of the smaller inner rims present in some of the bays.

Summary and Conclusions

This article represents the results of extensive geological field investigation over much of the

Coastal Plain area since 1933. The field work was supplemented by a complete coverage of the area containing Carolina Bays and bordering regions by means of aerial photographs. An attempt was made to summarize and critically analyze the principle geologic work on the Bays to date, including all major theories of origin.

After approaching the problem from many directions, the meteoritic theory of origin of the Carolina Bays appears increasingly tenable. Recent work envolving statistical studies of such bay features as lineation, ellipticity, and orientation add considerable strength to this theory. A meteoritic theory accounts for at least 13 major characteristics not so far satisfactorily explained by the various terrestrial type theories of bay origin. Solution and wind action, which form bases for some terrestrial theories, are recognized by the writer to be effective processes in some places, but were observed to be merely modifying action upon existing Bays.

The Revised Meteoritic Theory (air-shock wave) was proposed by the writer to better explain some observed phenomena. Among the exponents of terrestrial theories, it is often contended that the larger bays measuring several miles in diameter are large in comparison to known meteor craters, and that meteors of such size would probably explode on contact with the earth, giving circular instead of elliptical craters. Under the Revised Meteoritic Theory, the meteor is assumed to be much smaller than its resulting crater, since the air-shock wave accompanying the meteor acting on loosely consolidated Coastal Plain sediments removed considerably more material than the impact of the meteor itself. Meteors of comparable size would yield much smaller craters in consolidated rock. Laboratory experiments with high-powered projectiles fired into stratified material simulating Coastal Plain sediments duplicate in a striking manner the ellipticity and rim characteristics of the Carolina Bays and also indicate the effectiveness of air-shock waves in crater developments.

A detailed study of multiple and heart-shaped bays indicates that they occur largely in definite patterns explained most satisfactorily by the infall of tandem meteorites striking the eastward-rotating earth at angles probably around 30° to 35° to the earth's surface. None of the terrestrial theories offered to date account satisfactorily for the overlap patterns of multiple bays.

The Carolina Bays are observed to be restricted in time and geographic distribution (a portion of the Atlantic Coastal Plain). The time differential of the origin of overlapping bay rims is considered to be a matter of seconds, or split seconds. The origin of the bays may be observed to be in no way dependent on or a result of the nature of the physiography—a fact not in keeping with terrestrial theories. They are confined to the Coastal Plain apparently because of better preservation in Coastal Plain sediments where weathering has been less extreme than in the bordering Piedmont area to the northwest. The great concentration of adjacent meteoritic material found in the latter area is considered a likely part of the meteoritic shower forming the Carolina Bays. Under any terrestrial theory, their occurrence adjacent to the Coastal Plain would have to be considered strictly coincidental to the origin of the Carolina Bays.

Magnetometer surveys of the bays to date have produced very favorable results in support of the meteoritic theory. All pronounced magnetic spot highs appear in logical positions relative to bays. Though additional work naturally is to be desired, it is thought that magnetic data collected is sufficient for general conclusions concerning the true significance of the magnetic anomalies.

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MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, SEPTEMBER 14, 1949.